

Construction noise monitoring

In the Ecowende HKW wind farm
Part 1: Measured sound levels

Client:
Ecowende

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1 INTRODUCTION

Ecowende is currently constructing the most ecological wind farm yet, as the construction of the HKW (Hollandse Kust West) lot VI wind farm includes a large number of measures that aim to mitigate negative ecological impacts and to stimulate positive impact. An extensive monitoring program has been set up to study the ecological impact of offshore wind farms and the effectiveness of the implemented measures.

A significant impact of offshore wind farms on marine mammals is related to the underwater noise that is emitted during the installation of its foundations. The foundations are traditionally installed by means of impact pile driving, a technique that results in high impulsive sound levels.

The harbour porpoise, the most abundant marine mammal species in the Ecowende wind farm area and the North Sea as a whole, is known to avoid unmitigated impact pile driving activities up to distances of 10–34 km due to these impulsive sound levels (Nehls et al., 2016; Geelhoed et al., 2018; Benhemma-Le Gall et al., 2021; Jong et al., 2022). The development and application of noise abatement and mitigation measures, required to meet noise thresholds that have been set by national governments in the past 10–15 years, has probably reduced this distance to typically 5–7 km (Nehls et al., 2016; Jong et al., 2022), although other research suggests that the range to the installation location is more important than the received sound level (Rose et al., 2019; Thompson et al., 2026).

In the Netherlands, regulatory thresholds for underwater noise emitted during pile driving activities are substantiated in the Framework for Assessing Ecological and Cumulative Effects (KEC, Heinis et al., 2025). The underwater noise threshold is based on a maximum acceptable harbour porpoise and seal population reduction as a result of the construction of offshore wind farms (the reduction should remain below 5% with a certainty of 95%). The population reduction is assessed through a modeling approach that includes dedicated models for the calculation of (1) emitted noise at the source, (2) propagation of noise into the environment, (3) probability of disturbance of animals using a dose-response relation, (4) the total number of disturbed animals using population density maps, (5) the reduction in population size using the interim PCoD (Population Consequences of Disturbance) model. The noise threshold for the construction of the HKW wind farm lots was set as a maximum Sound Exposure Level (SEL) of $SEL_{max} = 168 \text{ dB re } 1 \mu\text{Pa}^2\text{s}$ at 750 m from the pile, based on KEC 3.0 (Heinis et al., 2019). As a result of the acceleration in wind farm development in the North Sea and new scientific insights implemented in the calculation methodology, this threshold was lowered to $SEL_{max} = 164 \text{ dB re } 1 \mu\text{Pa}^2\text{s}$ for following wind farms in KEC 4.0 (Heinis et al., 2022) and KEC 5.0 (Heinis et al., 2025).

Thanks to these thresholds on emitted noise during the construction phase, the impact of pile driving on marine mammal populations is reduced to an acceptable level. However, the mitigation measures required to comply with the thresholds complicate offshore operations and increase the carbon footprint of projects, particularly when large bubble curtains are used. Recent innovation efforts focus on lowering sound levels at the source by developing on-hammer dampeners (e.g. Menck MNRU and IQIP Pulse) and innovative installation techniques. During the construction of the Ecowende wind farm, the Menck MNRU was used for all impact pile driving, in combination with a Hydro Sound Damper (HSD) net and a double Big Bubble Curtain (dBBC). The MNRU introduces elasticity between the hammer and the anvil, prolonging the impact pulse, and thereby reducing sound levels. The HSD-net and the dBBC change the local impedance of the seawater and introduce cavities with surface tension, resulting in reflection and absorption of the sound wave radiating from the pile.

Two innovative installation techniques were tested during the installation of 6 of the 52 monopiles: 3 monopiles were partially installed using a vibro hammer, and 3 monopiles using a combination of a vibro hammer and jetting. These innovative techniques were compared to conventional techniques via an underwater noise monitoring campaign that was executed during the construction phase of the wind farm, where the emitted sound levels were compared for the

installation of similar monopiles.

The 52 foundations of the Ecowende wind farm were installed by the Boreas, a jack-up vessel of Van Oord, with a capacity of 4 monopiles per trip. During installation (Figure 1.1), a monopile was lifted out of its storage and set securely into the vessel's gripper. The hammer was then attached to the main crane and lifted into position. The HSD-net was attached to the gripper and the dBBC was deployed and operated by a dedicated noise mitigation vessel. The secondary steel was added by the Boreas after installing the foundation to its final penetration depth. Further installation works (Figure 1.2) and inspection related to the foundation and secondary steel were carried out by a Service Operations Vessel (SOV): the Vestri Enabler of Edda Wind. This vessel was also used by Van Oord for the deployment and retrieval of the noise monitoring setups.



Figure 1.1: Impression of monopile installation works and measurement campaign, pictures taken from the Boreas. a) The impact hammer ready to be installed on top of the pile. b) The noise mitigation vessel with the bubble curtain active. c) The pile in the gripper with the HSD-net deployed and the dBBC in the background. d) Installation of the near-pile monitoring setup from the Boreas.



Figure 1.2: Impression measurement campaign works from the Vestri Enabler. a) The SOV in the field close by the Boreas during deployment of the setup. b) Setup retrieval at night. c) Setup laid out on deck. The snatch blocks were used for deployment.

High quality data of the installation techniques and mitigation measures was collected during this extensive measurement campaign. Data processing is the basis for analysis and interpretation, and as a result, the processing and interpretation of the data has been separated in two different reports. A description of the content of both reports is given below.

- **Report 1:** This report contains details on the measurements, the measuring equipment and the data processing pipeline. This report focuses on data processing and showcases the data. Measured broadband levels are shown alongside spectral results. For impact piling care has been taken to ensure that pulses measured at different measurement locations correspond to the same hammer blow. This allows for detailed analysis per blow. For continuous sound the broadband sound pressure levels are shown together with driving frequency and penetration. Spectral results are shown at given times to showcase the quality and use cases of the data. The aim of this report is to create a basis for further data analysis. The processed data is used in the second report but can also be used by other parties for their own research interests. The goal can be summarised as:

Describe the data processing method and showcase the resulting processed data.

- **Report 2:** Interpretation of the analysed data. This report focuses on the derivation of key quantities from the processed data, such as bubble curtain and HSD net effectiveness, as well as directionality and mitigation measure interaction. The goal of this analysis is to gain insight into the relevant parameters for resulting sound levels of multiple installation techniques and mitigation measures. A secondary goal of the second report is to use the measurements to evaluate assumptions in the current Dutch framework to calculate impact of underwater noise (KEC). Within the KEC framework a noise footprint translates into a number of disturbed harbour porpoises, depending on the loudness and spectral characteristics of the emitted noise. The impact of the different installation techniques on marine life is compared within this framework based on the measured data. The focus is on the characteristics of emitted underwater noise; the harbour porpoise response (dose-response curve) is discussed in a separate report. The goal of the second report can be summarised as:

Acquire technical insight into emitted sound levels for different piling techniques,

mitigation measure effectiveness and potential implications for the KEC framework.

This report starts with the measurement plan. Then the data processing methodology is outlined, and finally the results are shown for different installation techniques.

2 MEASUREMENT PLAN

Multiple installation techniques were used during the installation of the monopile foundations in the Ecowende wind farm: the traditional impact hammering and the more recently developed methods of vibro driving and Vibrojet® driving. Underwater sound measurements were conducted that aimed to attain insight into different aspects of these three techniques. For impact hammering the objectives were to describe the effectiveness of the different mitigation measures and to investigate noise propagation over larger distances. For vibro driving and Vibrojet® driving the aim was to measure the (unmitigated) emitted noise and its propagation. This chapter outlines how these objectives were translated into a measurement plan.

2.1 Measurement locations

Measurements were performed at multiple measurement stations (Figure 2.1). Each station had a particular purpose:

- The two stations closest to the foundation were used to determine the efficacy of the mitigation measures.
- The two stations farthest from the foundation were used to obtain insights into noise propagation.
- The four stations at 750 m from the foundation were used for sound profile measurements and to determine directional variability. Two of these stations were due to Van Oord (executed by ITAP). The data of these stations is not used in this report but is available for report 2.

The local bathymetry and local bubble curtain properties could influence the received sound levels in different directions. The stations at 750 m from the foundation were also used to capture this possible directional dependence. For impact pile driving, all depicted stations were deployed; for vibro/Vibrojet® driving, the nearest locations (blue) were not required. They were opportunistically deployed in some cases.

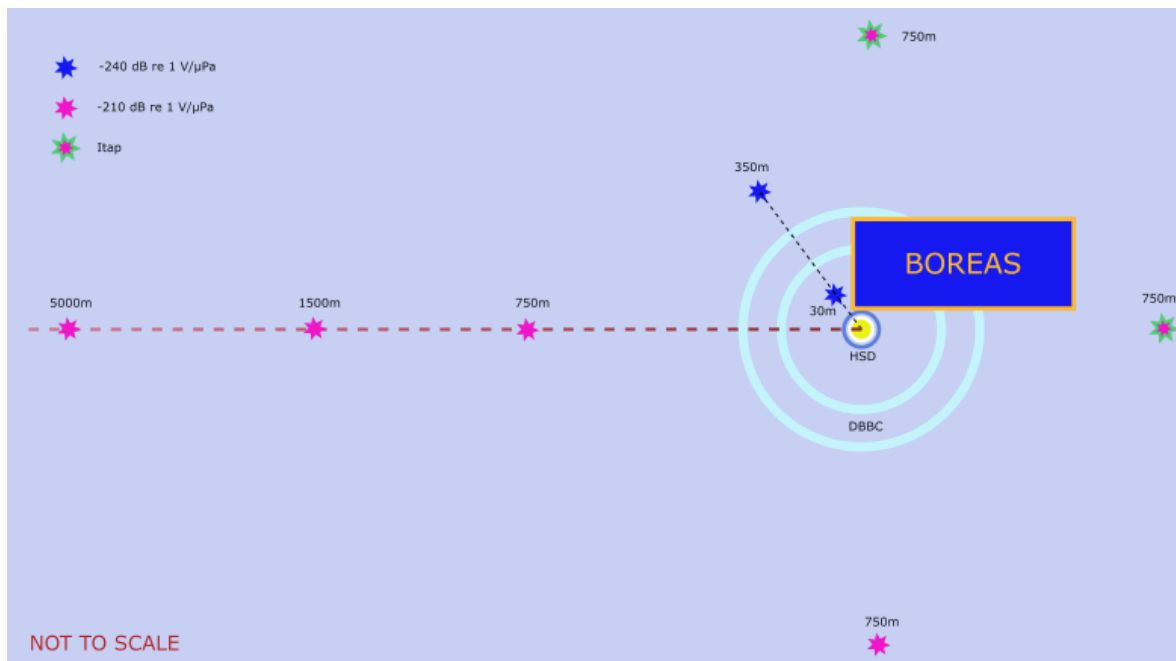


Figure 2.1: Overview of the typical measurement positions (stars) relative to the monopile foundation (yellow dot). The mitigation measures indicated are the HSD (dark blue circle around foundation) and the dBBC (light blue circles). The colors of the measurements stations correspond to the hydrophone sensitivity.

The idealised locations shown in Figure 2.1 were subject to practical considerations, such as the requirement for the stations to be within the wind farm, or the requirement to not be too close to array cables. Consequently, measurement locations could slightly deviate from their idealised locations.

The inner and outer bubble curtain hose have a length of 720 m and 930 m respectively. This corresponds to an equivalent radius of 115 m and 148 m respectively, the radial difference corresponding to approximately the water depth.

2.2 Measurement setups

Eight stations were deployed in total, seven of which were deployed using buoys (Figure 2.2a): 5 by Waterproof and 2 by ITAP. The eighth station (Figure 2.2b) was deployed from the aft of the Boreas and stayed connected to a strong point. The setups are in accordance with ISO:18406 on the measurement of radiated underwater noise from percussive pile driving (International Organization for Standardization, 2017b).

The recorders (RTsys EA-SDALP) and hydrophones (HTI96-min, sensitivity -210/-240 dB re 1V/μPa) were attached to a Dyneema mooring rope that connected the anchor to a surface buoy. To ensure tension, two subsurface floats were attached to this line, with a combined volume of approximately 20 L. An additional lighter pick-up buoy was attached to aid in retrieving the setup. The setup was kept upright by a weight at the bottom. The recorder and hydrophone were separated by almost a metre to minimise the impact of the air-filled recorder on the measurements. The hydrophone was placed in a cage that was attached directly to the line. Possible disturbance due to flow noise was not considered an issue due to the high sound levels to be measured.

In the Boreas measuring setup, tension in the line was ensured by its attachment to the strong point. The actual location of the hydrophones in this setup could be affected by current: any slack in the line leads to slightly larger depths than expected based on a fully vertical line. Several conductivity temperature depth (CTD) sensors were attached to the line to verify the (approximate) depth of the hydrophones. In addition to the local depth, the CTD sensors are also relevant for calculating the local sound speed profile. A total of four hydrophones were used; due to the

close vicinity of the setup to the sound source, the sound field is still rather inhomogeneous and therefore depends on the depth.

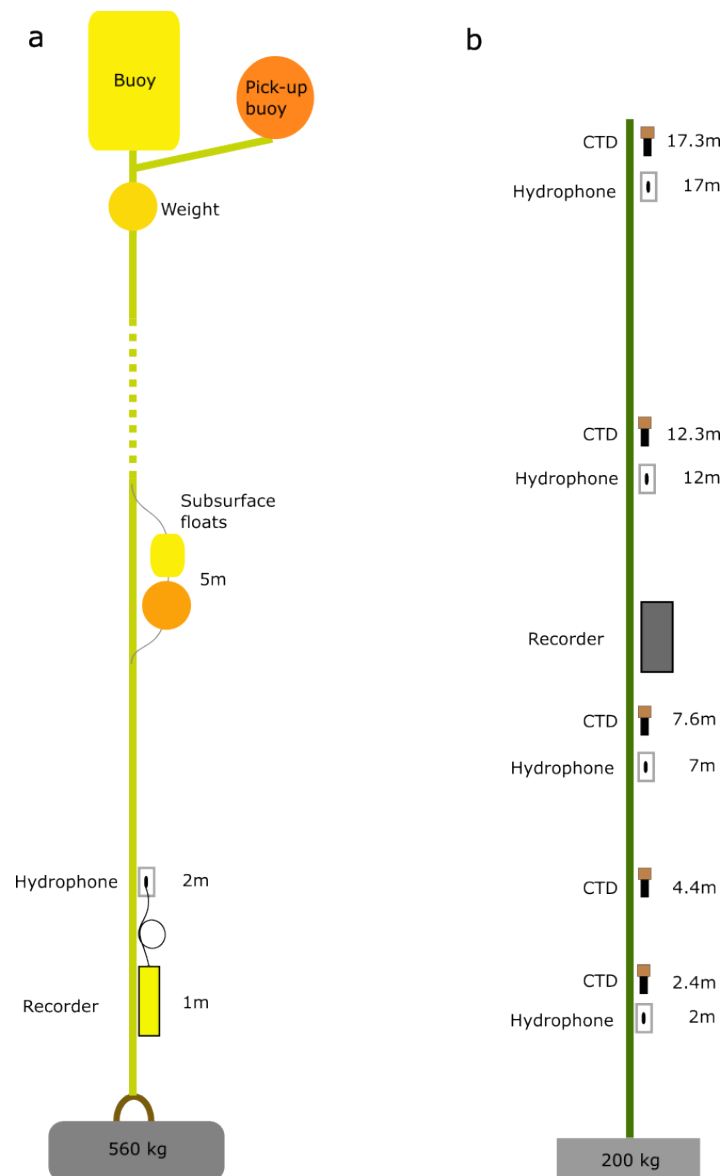


Figure 2.2: Schematics of the different setups used. a) buoy setup; b) Boreas setup. The cables from the hydrophones to the recorder are disregarded for readability of the Boreas setup.

2.3 Pile specific scenarios

Three installation methods were used:

- Impact hammering (Menck S3500) on 46 + 4 locations
- Vibro driving (VLT CV 640 quad) on 3 locations
- Vibrojet® driving (VLT CV 640 quad + GBM jet) on 3 locations

The number of piles installed with each installation technique is added in the itemisation (total of 52 piles installed). Additional impact hammering was necessary to reach the final penetration depth for the three vibro-driven piles and one of the Vibrojet®-driven pile, adding up to a total of four. In total 46 piles were fully installed using impact hammering. Out of the measured pile installations, 6 scenarios were selected (Table 2.1): three for impact-driven piles, two for vibro-driven piles, and one for Vibrojet®-driven piles. All monopiles were designed such that, if

required, they could be brought to final penetration depth using the impact hammer. The combinations of monopiles and installation locations were decided upon by the client, contractor, and subcontractors, monopile diameters depend on the turbine height.

*Table 2.1: Overview of the measured scenarios, * indicates vibro/Vibrojet® piles that have reached final penetration depth using impact pile driving*

Pile ID	Driving type	Scenario	Diameter
G2	Impact	1a	9.3m
G5*	Vibro	5	9.3m
A1	Impact	1b	9.3m
A3*	Vibro	5	9.3m
A3	Impact	4	9.3m
F1*	Vibro	6	9.3m
L3*	Vibrojet®	7	8.8m
L4	Vibrojet®	7	8.8m
L2	Vibrojet®	7	8.8m

The non-consecutive numbering of the scenarios is a result of conformation to the labeling during the measurement campaign. Pile A3 started off with vibro driving, but when close to the maximum reachable penetration depth, the vibro tool was switched out for the impact hammer. Scenario 4 was then performed using the impact hammer. The pile IDs are listed in chronological installation order.

The execution of these scenarios was approved in advance by the relevant regulatory authorities. The durations of measurements with partial mitigation were kept as short as possible to reduce their environmental impact as much as possible while ensuring high quality data. The scenarios are described in more detail in the following subsections.

2.3.1 Impact pile driving scenarios

The scenarios are labeled as 1a, 1b and 4 for impact pile driving. The scenarios involve:

- 1a Fully mitigated → Without dBBC but with HSD → Without dBBC and without HSD
- 1b Fully mitigated → Without HSD but with dBBC → Without dBBC and without HSD
- 4 With dBBC → Without inner ring dBBC with outer ring dBBC → without dBBC

Scenario 1a was executed as follows:

- Normal mitigated piling until 20 minutes of piling remains
- Piling was paused and the dBBC is switched off. Piling operations are paused for 25 minutes to make sure all bubbles have drifted away
- Piling was resumed without the dBBC but with the HSD net for 8 to 10 minutes
- Piling was paused until the HSD net is fully retracted
- Piling was resumed without the dBBC and without the HSD net for 8 to 10 minutes

Scenario 1b was similar to 1a, but the HSD net was retracted first and then the dBBC was switched off.

Scenario 4 was executed as follows:

- Partial mitigated piling, with the dBBC employed but without the HSD-net, until 20 minutes of piling remains
- Piling was paused and the inner ring of the dBBC is switched off. Piling operations are paused for 25 minutes to make sure all inner ring bubbles have drifted away

- Piling was resumed with only the outer ring of the dBBC for 8–10 minutes
- Piling was paused for 25 minutes and the outer ring of the dBBC is switched off.
- Piling was resumed without the dBBC for 8–10 minutes

In summary, for each of these tests piling started with the mitigation measures employed. For the last 20 minutes of piling, the mitigation tests took place. The mitigation measures were shut off in two steps. Each step resulted in roughly 10 minutes of piling data with subsequently less mitigation. The time between each measurement is roughly 25 minutes; this is for the bubbles to drift away or for the HSD-net to be retracted. These scenarios were designed in line with Deutsches Institut für Normung (DIN) (2017).

The Menck MHU 3500S hammer (max 3500 kJ impact energy with a 175t ram mass weight) was used for all impact driving scenarios. This hammer was equipped with a Menck Noise Reduction Unit (MNRU); unmitigated impact hammering was not tested. The use of the MNRU does not hinder the investigation of the effectiveness of the dBBC and the HSD net.

2.3.2 Vibro and Vibrojet® scenarios

The following scenarios were used for vibro driving:

- 5 Unmitigated
- 6 HSD net deployed

Scenario 5 has no mitigation measures during vibro driving, resulting in a dataset containing unmitigated vibro driving for various operational parameters.

Scenario 6 is similar to scenario 5 but with the HSD-net deployed, resulting in a dataset of partially mitigated vibro driving for various operational parameters.

For Vibrojet® driving unmitigated levels were measured:

- 7 Unmitigated

Scenario 7 has no mitigation measures during Vibrojet® driving, resulting in a data set containing unmitigated Vibrojet® driving for various operational parameters.

The Cape Holland VLT CV-640 QUAD vibro hammer was used for all vibro and Vibrojet® scenarios. The GBM Works jetting system was used in addition to the vibro hammer.

3 DATA PROCESSING APPROACH

The data processing methodology depends on the installation method (impulsive noise or continuous noise). This chapter is split into one part for each method.

The nature of the noise produced by the installation depends on the installation technique: for impact hammering it is considered impulsive; for vibro-driving and Vibrojet®-driving it is considered continuous. Impulsive sound is characterised by peaks in the sound level, surrounded by periods of lower sound levels. Continuous sound is characterised by persistent sound levels over the considered time scale. Continuous sound can vary in time, but on much larger time scales than impulsive sound.

Because of this difference in nature, different metrics are used to describe the sound levels. For the impulsive noise from impact piling the single strike sound exposure level (SEL_{SS}) is used:

$$SEL_{SS} = 10 \log_{10} \frac{1}{\Delta t_0} \int_{\Delta t_{strike}} \frac{p(t)^2}{p_0^2} dt \quad [\text{dB re } 1(\mu\text{Pa})^2 \text{ s}] \quad (3.1)$$

With $\Delta t_0 = 1$ s the reference duration, Δt_{strike} the time interval in which 100% of the pulse energy due to a single hammer strike is contained, $p(t)$ the sound pressure in time (t), and $p_0 = 1 \mu\text{Pa}$ the reference pressure. SEL_{SS} can be interpreted as a measure of the intensity of the pulse due to the hammer strike, integrated over the time.

The continuous noise from vibro-driving and Vibrojet® -driving is better represented by the sound pressure level (SPL). This is defined as:

$$SPL = 10 \log_{10} \frac{1}{\Delta t} \int_{\Delta t} \frac{p(t)^2}{p_0^2} dt \quad [\text{dB re } 1(\mu\text{Pa})^2] , \quad (3.2)$$

with Δt the averaging time.

Measurements are processed following ISO:18406, (International Organization for Standardization, 2017b) and definitions of the different measures for sound are in line with ISO:18405 (International Organization for Standardization, 2017a).

3.1 Processing of impulsive noise data

Noise generated during impact pile driving is considered impulsive. This impulsive noise is characterised by the SEL_{SS} (eq. 3.1) of each hammer blow. Since hammer blows are usually 2 seconds apart, the analysis window length is set to 1 second. This is sufficiently long to capture the entire blow, even at larger distances from the pile, and not too long for the next blow to also be part of this interval. Because the background sound level can change over time, it is determined for each blow from a half-second window before the blow window (Figure 3.1).

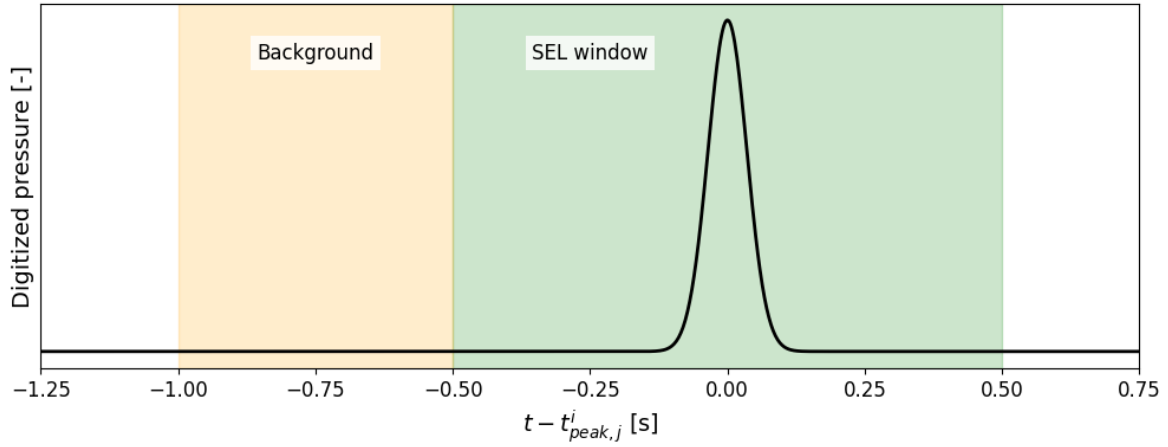


Figure 3.1: Schematic representation of the windows used to determine background level and the single-strike sound exposure level (SEL_{SS}).

Let $i \in \{1, \dots, N\}$ denote each blow number, with N the final blow of a pile's installation. $j \in \{1, \dots, M\}$ denotes the deployed recorder with its hydrophone(s), with M the total number of recorders deployed in the field. $t_{peak,j}^i$ denotes the i^{th} peak recorded by the j^{th} recorder. The peaks in the time series were automatically detected by a peak detection algorithm. To ensure that detected peaks in the measurements at each recorder correspond to the same piling blow, the following procedure was followed:

- One of the recorders at 750m was taken to be the reference recorder.
- The time corresponding to the final blow (the N^{th} peak) was determined for each recorder.
- The timeseries for each recorder was corrected by the difference between its detection of the N^{th} peak and that of the reference recorder. Differences are in the order of seconds and can, for example, be due to minor differences in the set clock time, but are also due to different sound travel times to the deployed recorders.

As an example, the peak times for the second recorder are given by eq 3.3 with the first recorder being the reference recorder.

$$t_{peak,2}^i = t_{peak,1}^i + (t_{peak,2}^N - t_{peak,1}^N) \quad (3.3)$$

The SEL_{SS} values for each blow were calculated in decidecade bands for each recorder, using the $t_{peak,j}^i$ values to determine the time windows. These levels provide insight into the spectral content of each detected piling blow at all locations. The background value (SEL_{back}) was determined as the 5th percentile of all background values falling within a minute prior to the blow and a minute after the blow (eq 3.4).

$$SEL_{back,corr,j}^i(f) = [SEL_{back,j}^{i-1min < i < i+1min}(f)]_5 \quad (3.4)$$

The SEL_{SS} of a frequency band is not taken into account if SEL_{back} and SEL_{SS} are less than 3 dB apart in that band.

Although not the main results of the impact measurements, the SPL was plotted alongside the SEL_{SS}. The SPL values were determined using a rectangular window (ISO18431-2, International Organization for Standardization, 2004) as to make sure the peak is not filtered out. The shown SPL values are the moving (pressure) mean over all SPL values over a 30-second window.

3.2 Processing of continuous noise data

Noise generated during vibro-driving and Vibrojet[®]-driving is considered continuous. This continuous noise is characterised by its SPL (eq. 3.2), which is calculated in frequency bands (eq.

3.5):

$$SPL(f_c) = 10 \log_{10} \left(\frac{\int_{f_l}^{f_u} P^2(f) df}{p_0^2} \right) dB \quad (3.5)$$

where f_c is the frequency band's centre frequency, f_l and f_u are the lower and upper bound of the frequency band, and $P(f)$ is the sound pressure spectrum. The sound pressure spectrum is calculated using the Hanning window (ISO18431-2, International Organization for Standardization, 2004) to prevent spectral leakage.

The continuous noise sources are processed in hybrid millidecade bands (Martin et al., 2021). In this approach, frequency bands for frequencies below 456 Hz have integer centre frequencies and a bandwidth of 1 Hz. Starting at 456 Hz, the center, lower, and upper frequencies of the k^{th} band are given as millidecades (eq. 3.6).

$$f_{c,k} = f_0 10^{k/1000}, \quad f_{l,k} = f_{c,k} 10^{-1/2000}, \quad f_{u,k} = f_{c,k} 10^{1/2000} \quad (3.6)$$

The lower frequency for data processing was $f_0 = 8$ Hz; with a 1-second window, lower frequencies can no longer be reliably determined. Moreover, below 8 Hz, no significant energy is transformed into emitted sound.

4 IMPACT RESULTS

This chapter describes the results of the data processing of the three impact piles. The data are presented as the broadband SEL_{SS} in time. Spectral results are shown at certain indicative times.

4.1 G2, scenario 1a

Scenario 1a was tested on impact pile G2 (2.1). The noise mitigation deployed was:

- **10:30-11:50** fully mitigated, dBBC and HSD
- **12:30-12:40** partially mitigated, HSD
- **13:05-13:25** no mitigation (apart from on-hammer dampener)

Figure 4.1 shows the broadband SEL_{SS} during the installation. The coloured shading corresponds to the deployed mitigation measures.

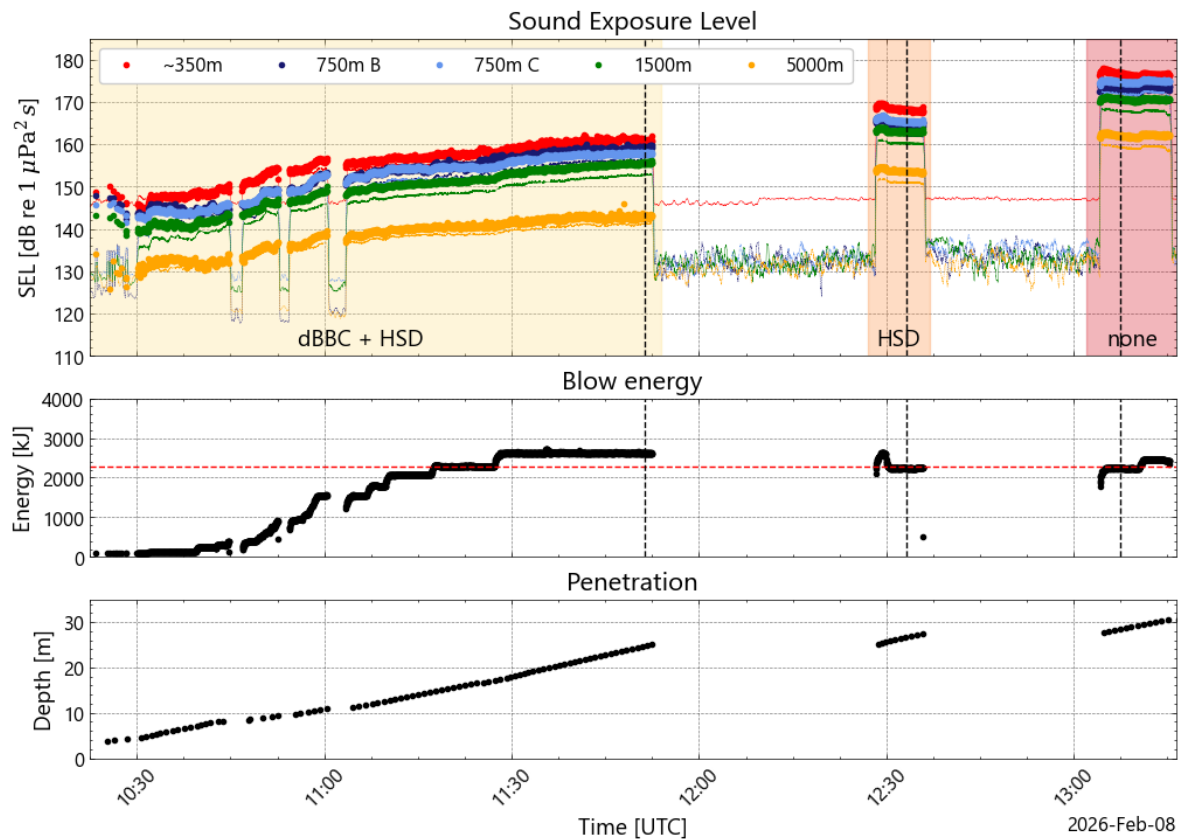


Figure 4.1: Broadband SEL_{SS} for pile G2 at different locations around the pile, along with the hammer energy and the penetration depth. The dots represent the broadband SEL_{SS} per blow; the solid lines are the accompanying (moving average) SPL.

The initial increase in SEL_{SS} can be explained by the increase in piling energy and by the increase in penetration depth. Once the dBBC is shut off, the SEL_{SS} increases by 5–6 dB. When the HSD net is also retracted, the SEL_{SS} increases by another 8–9 dB.

For the latter two times at which the dashed black lines are plotted, the piling energy is roughly the same. The first dashed black line has a roughly 15% higher impact energy corresponding

to 0.6 dB as compared to the other black dashed lines (see the red dashed line in the energy plot). However, in spite of differences in penetration depth, these three times are considered suitable to compare different mitigation measures. Figure 4.2 shows the decidecade spectrum of the SEL_{SS} at the three moments marked in Figure 4.1.

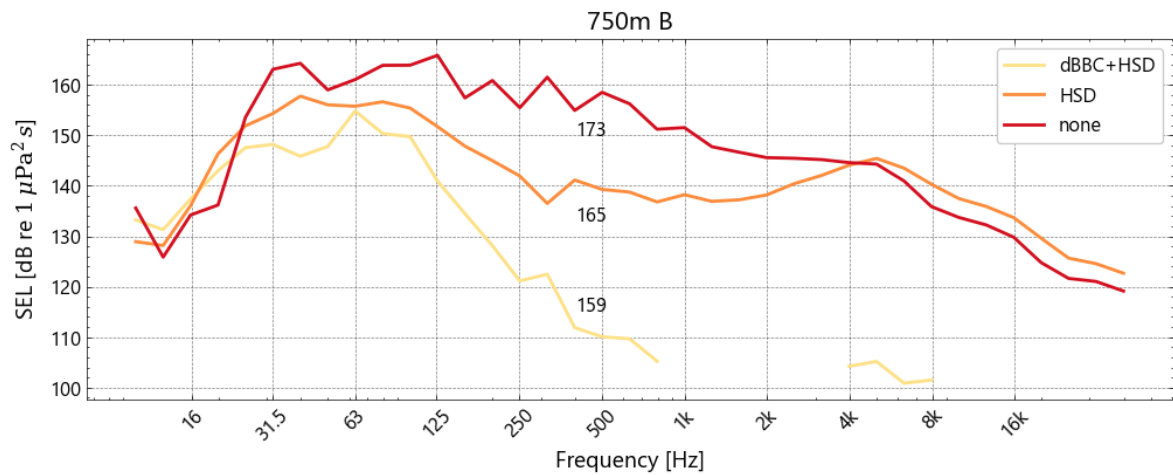


Figure 4.2: Decidecade spectrum of the SEL_{SS} at 750m from the pile for different mitigation measures. The broadband SEL_{SS} values for each mitigation measure are annotated next to their lines. The lines are interrupted wherever the measured level does not exceed the background level by at least 3 dB.

The effect of the HSD net is mainly visible in the 30 Hz–2 kHz range. The bubble curtain is effective over the entire range: from 30 Hz to 16 kHz; the higher frequencies are dampened most effectively. By subtracting the spectrum of the HSD net-only case from the spectrum of the unmitigated case, an estimate of the spectral effectiveness of the HSD net was made (Figure 4.3).

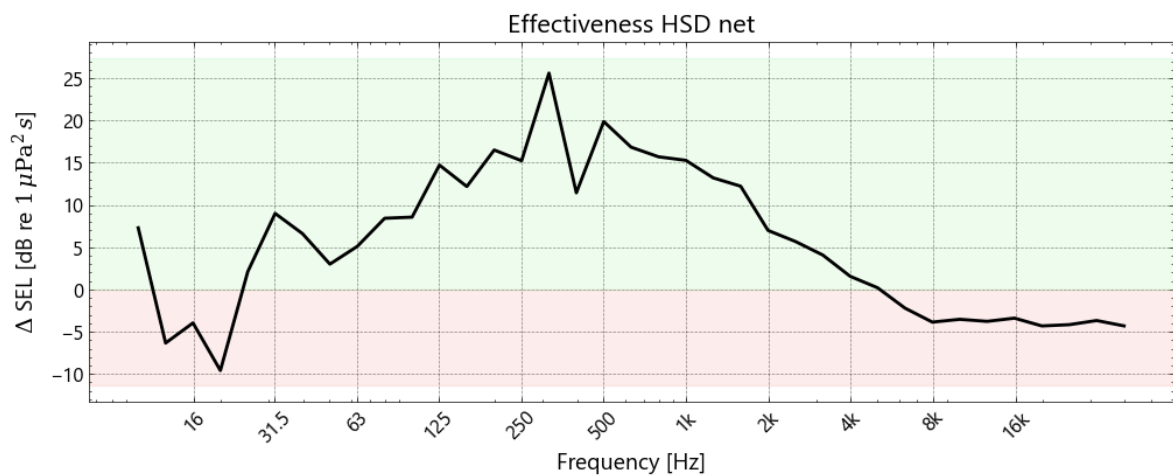


Figure 4.3: Difference between SEL_{SS} for the HSD-net-only case and the unmitigated case in decidecade frequency bands.

The unmitigated case is used to study propagation (Figure 4.4). As the distance to the pile increases, SEL_{SS} values decreases across the entire spectrum.

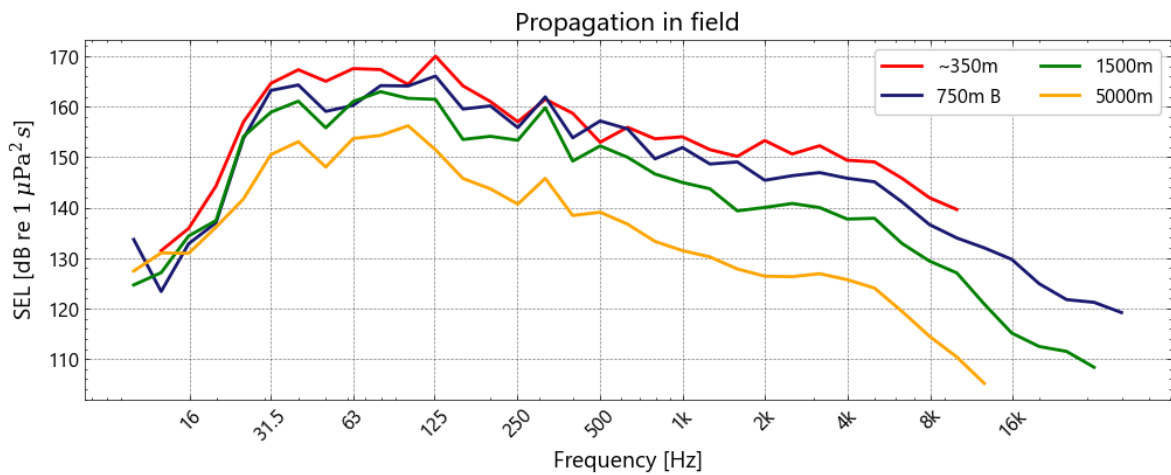


Figure 4.4: Decade SEL_{SS} spectrum measured at different distances from the same blow.

Near-pile measurements (Figure 4.5) show a similar pattern as measurements conducted at larger distances: SEL_{SS} increases with increasing piling energy and with increasing penetration depth. Shutting down the dBBC does not affect these measurements, as these measurements were performed within the dBBC. SEL_{SS} increases by about 10 dB when the HSD net is retracted.

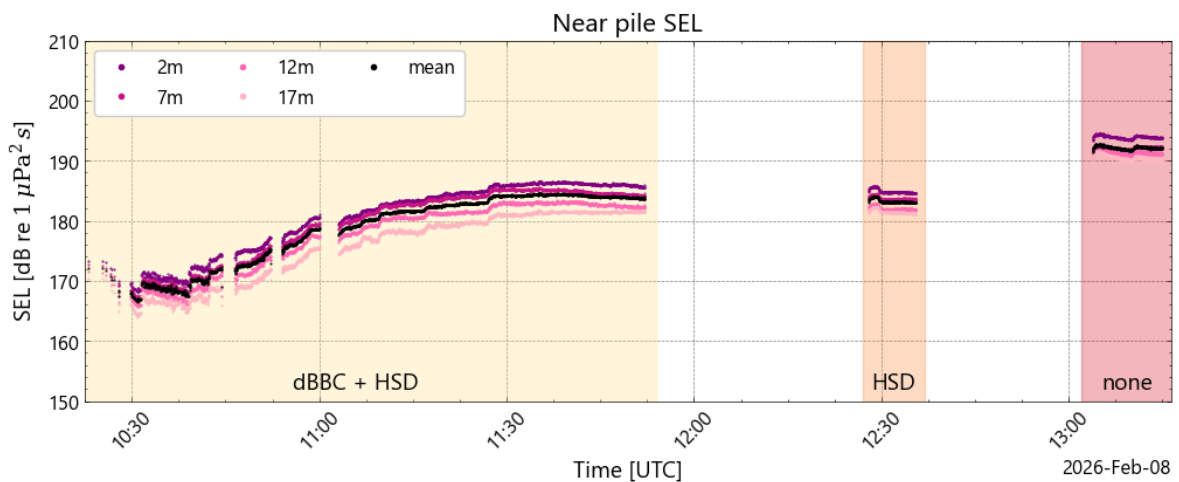


Figure 4.5: Broadband SEL_{SS} near the pile at various distances from the seabed.

4.2 A1, scenario 1b

Scenario 1b was tested on the impact pile A1 (2.1). The noise mitigation deployed was:

- **13:40-14:55** fully mitigated, dBBC and HSD
- **15:20-15:35** partially mitigated, dBBC
- **16:00-16:15** no mitigation (apart from on-hammer dampener)

Figure 4.6 shows the broadband SEL_{SS} during the installation. The coloured shading corresponds to the deployed mitigation measures.

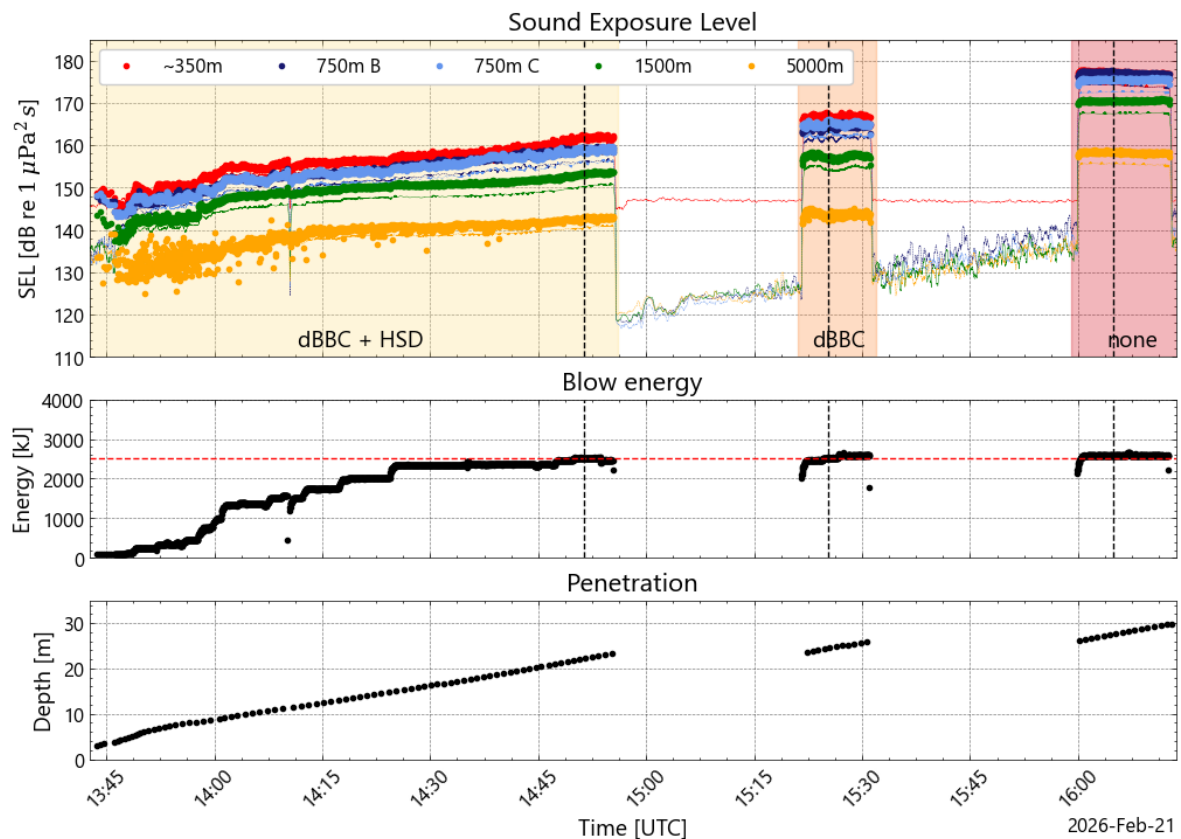


Figure 4.6: Broadband SEL_{SS} for pile A1 at different locations around the pile, along with the hammer energy and the penetration depth. The dots represent the broadband SEL_{SS} per blow; the solid lines are the accompanying (moving average) SPL.

The SEL_{SS} increases with blow energy and penetration depth. Once the HSD-net is retracted, the SEL_{SS} increases by 5–6 dB. When the dBBC is shut off, SEL_{SS} increases by another 12 dB.

Figure 4.7 shows the decade spectrum of the SEL_{SS} at the three moments marked by the black dashed lines in Figure 4.6.

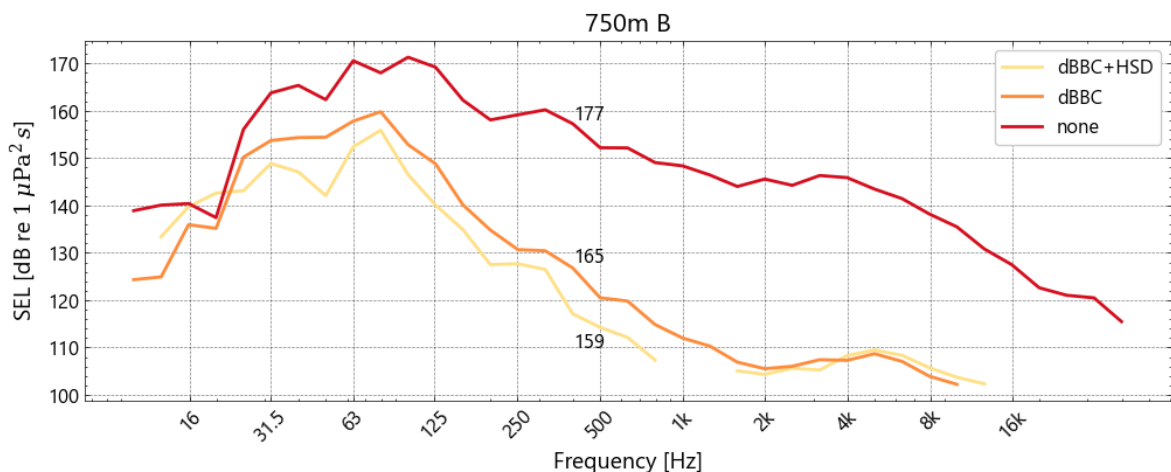


Figure 4.7: Decade spectrum of the SEL_{SS} at 750m from the pile for different mitigation measures. The broadband SEL_{SS} values for each mitigation measure are annotated next to their lines. The lines are interrupted wherever the measured level does not exceed the background level by at least 3 dB.

There is a large difference in the SEL_{SS} spectra of the unmitigated case and the dBBC-only case. The dBBC significantly dampens frequencies above 100 Hz, and dampens frequencies between

20 Hz and 100 Hz to a lesser degree. The HSD net provides additional damping for almost all frequency bands. By subtracting the spectrum of the dBBC-only case from the spectrum of the unmitigated case, an estimate of the spectral effectiveness of the dBBC was made (Figure 4.8).

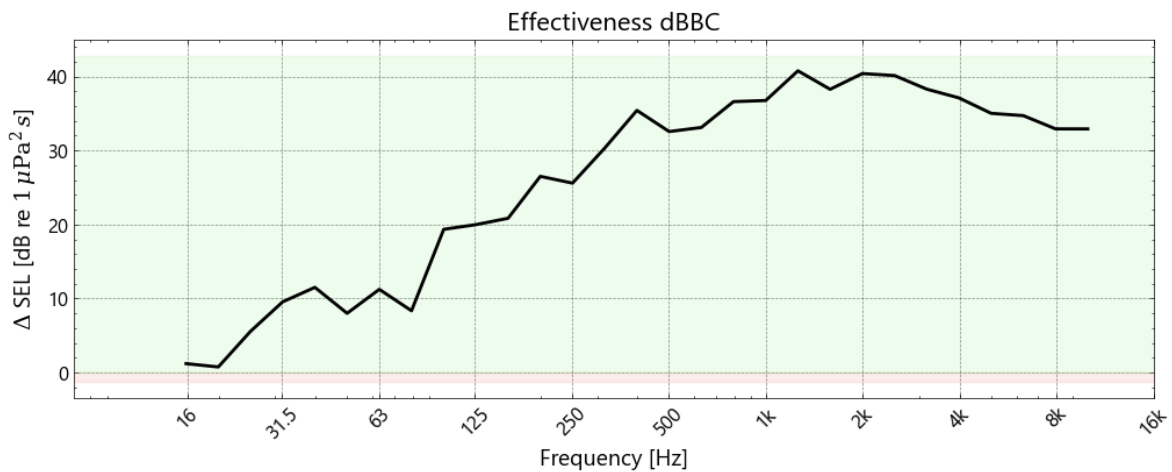


Figure 4.8: Difference between SELSS for the dBBC-only case and the unmitigated case in decidecade frequency bands.

In-field propagation (Figure 4.9) is shown along the line without mitigation, since the loudest blows carry the furthest. It seems that the directionality of the given blow resulted in a very comparable sound level at 350 m as compared to the level at 750 m. For distances beyond 750 m, SEL_{SS} decreases along the entire spectrum as the distance increases.

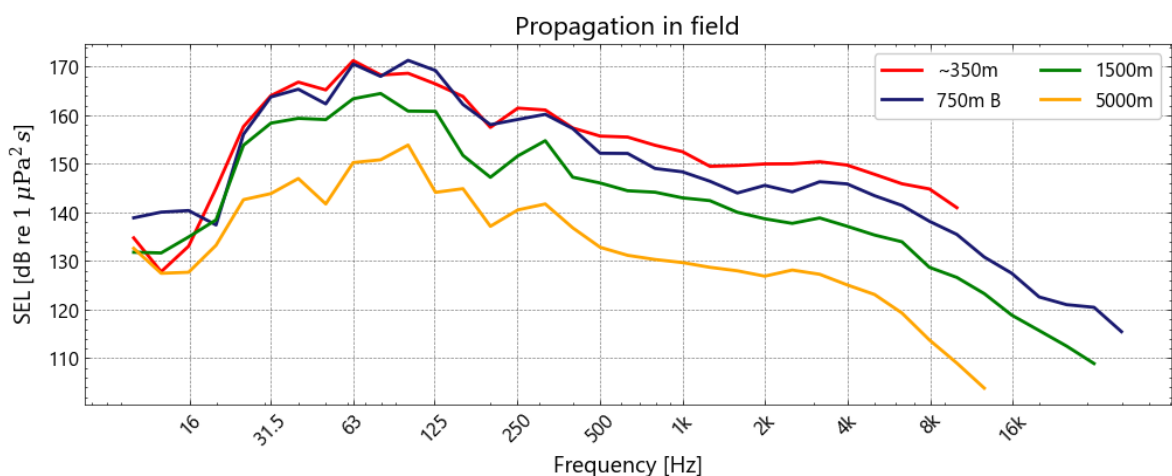


Figure 4.9: Decidecade spectrum of measurements taken at different locations of the same blow.

Near-pile measurements (Figure 4.10) show that the SEL_{SS} increases drastically once the HSD net is retracted. Because these measurements were performed within the dBBC, retracting the HSD net results in a situation where there is effectively no mitigation, even when the dBBC itself is still active. It is noted that the SEL_{SS} values with the dBBC deployed are slightly higher as compared to when there is no mitigation at all. This is probably due to reflections on the dBBC increasing the (low frequency) SEL_{SS} values within the dBBC.

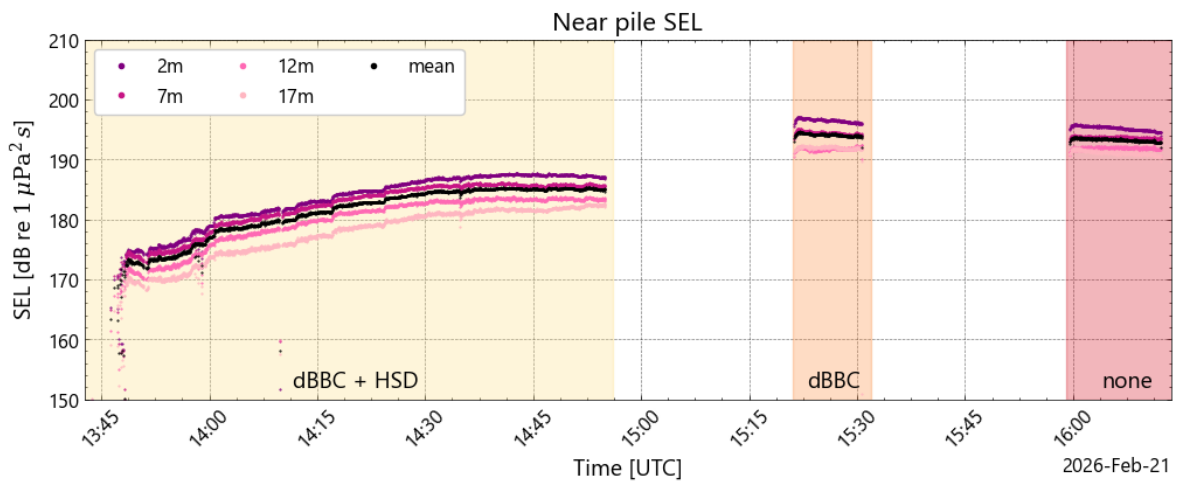


Figure 4.10: Broadband SEL_{SS} near the pile at various distances from the seabed.

4.3 A3, scenario 4

Scenario 4 was tested on the impact hammered part of pile A3 (2.1). The noise mitigation deployed was:

- **17:30-19:00** Partially mitigated, dBBC
- **19:30-19:40** Partially mitigated, only outer BBC active
- **20:10-20:30** no mitigation (apart from on-hammer dampener)

Figure 4.11 shows the broadband SEL_{SS} during the installation. The coloured shading corresponds to the deployed mitigation measures.

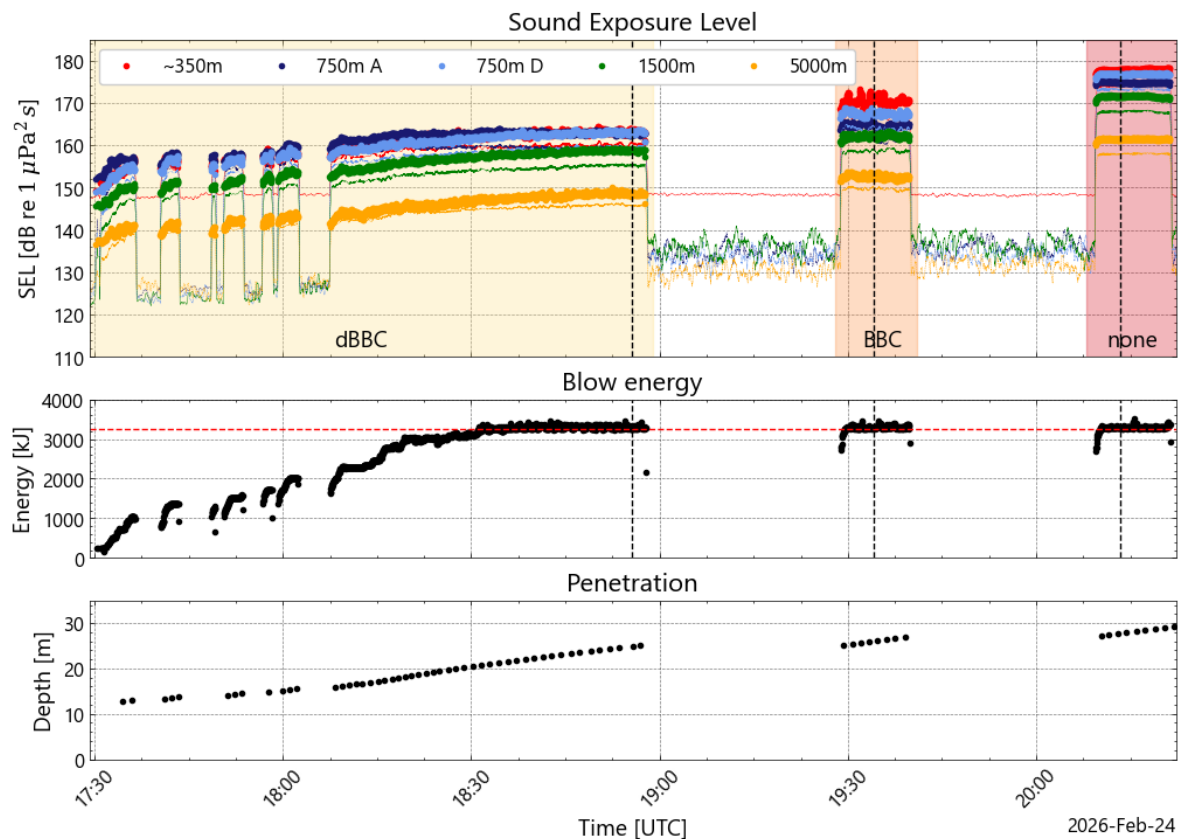


Figure 4.11: Broadband SEL_{SS} for pile A3 at different locations around the pile, along with the hammer energy and the penetration depth. The dots represent the broadband SEL_{SS} per blow; the solid lines are the accompanying (moving average) SPL.

The SEL_{SS} increases with blow energy and penetration depth. The first 12 m of the pile were vibro-driven and are not shown in the figure. Once the inner ring of the dBBC is switched off, the SEL_{SS} increases by 2–3 dB. The SEL_{SS} increases by another 10 dB when the outer ring of the dBBC is also shut off.

Figure 4.12 shows the decidecade spectrum of the SEL_{SS} at the three moments marked by the black dashed lines in Figure 4.11.

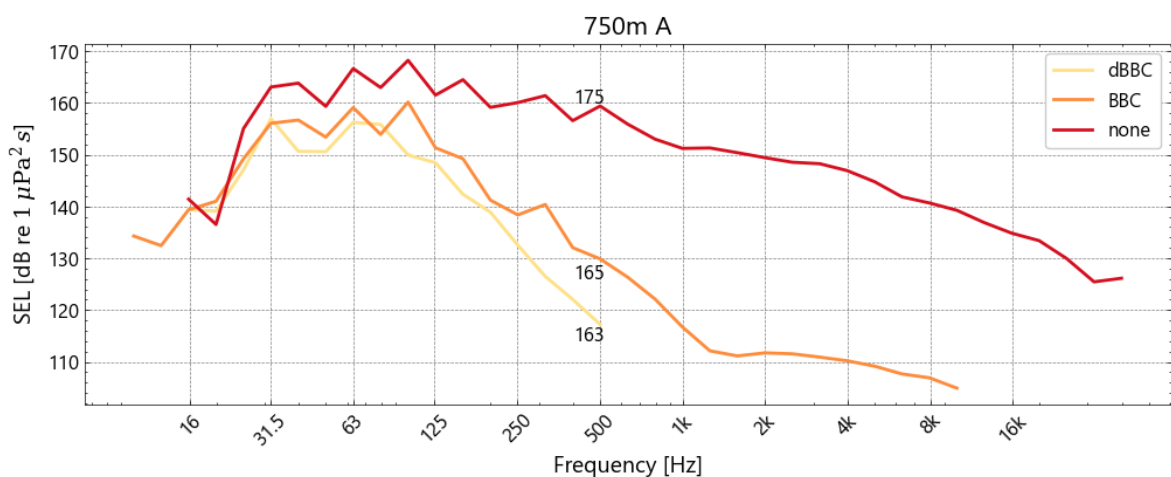


Figure 4.12: Decidecade spectrum of the SEL_{SS} at 750m from the pile for different mitigation measures. The broadband SEL_{SS} values for each mitigation measure are annotated next to their lines. The lines are interrupted wherever the measured level does not exceed the background level by at least 3 dB.

The difference in SEL_{SS} between the unmitigated case and the BBC case is much larger than the difference in SEL_{SS} between the BBC and the dBBC case. By subtracting the spectrum of the BBC and dBBC case from the unmitigated case, a comparison was made of their spectral effectiveness (Figure 4.13).

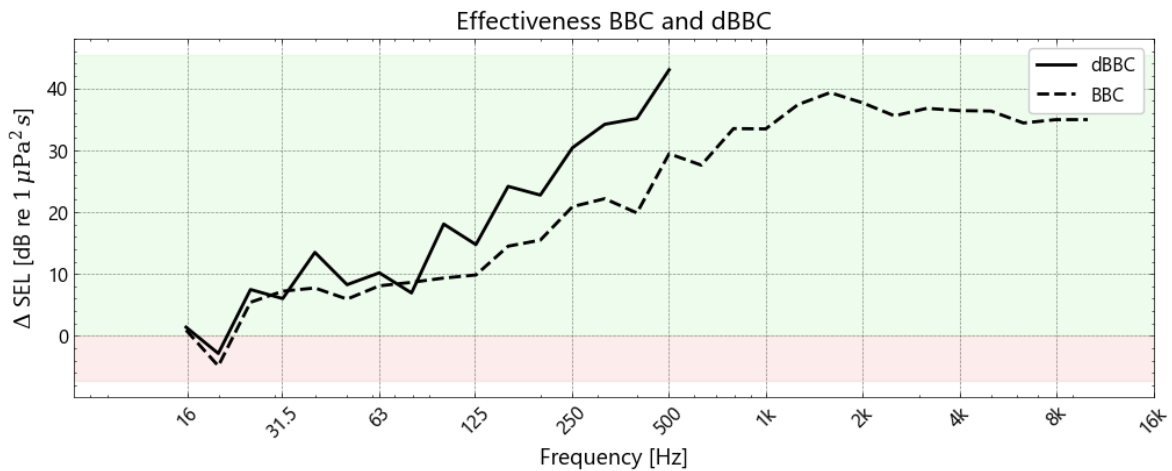


Figure 4.13: Decade spectrum of effectiveness of the dBBC and the BBC.

The dBBC outperforms the BBC mainly at frequencies above 250 Hz; above 500 Hz the sound levels are reduced too close to the background levels for an effectiveness to be calculated. The dBBC had a higher effectiveness in this measurement than in the previous one (Figure 4.8): at 500 Hz, the effectiveness is 40 dB compared to 30 dB. This could be due to a variability in the dBBC, but it could also be due to the small sample size. A follow-up on this report will delve deeper into these kind of observed variabilities.

Near-pile measurements (Figure 4.14) show that the SEL_{SS} values change very little between the dBBC, BBC, and unmitigated case; this is because these measurements were performed within the measurements were performed within the bubble curtains. The SEL_{SS} drops slightly when the dBBC is fully switched off, likely due a lack of reflection.

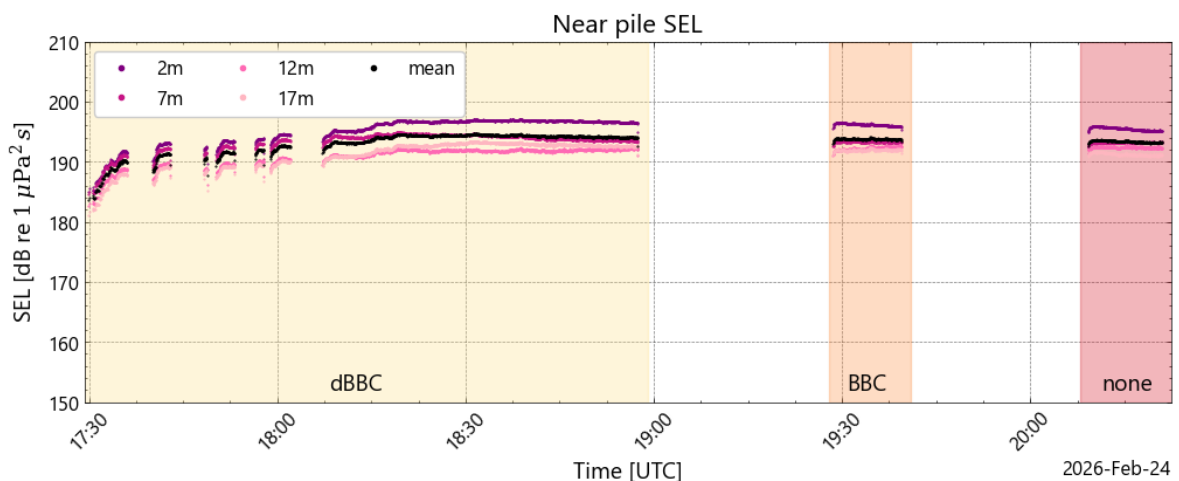


Figure 4.14: Broadband SEL_{SS} in time near the pile at different distances from the seabed.

5 VIBRO RESULTS

Two vibro piles are discussed in this chapter: A3, with no mitigation measures deployed, and F1, with the HSD-net deployed. G5 was initially vibro-driven, but is not considered here, as it concerns less than a minute of vibro driving. The vibro tool was stopped due to not being able to monitor pile stresses instantaneously.

5.1 A3, scenario 5

Scenario 5 concerns unmitigated vibro driving. Vibro pile A3 was driven on the 24th of February 2026 between roughly 9:51 and 10:06. It was driven to a penetration depth of 12 m until refusal. Figure 5.1 shows the broadband SPL during the installation.

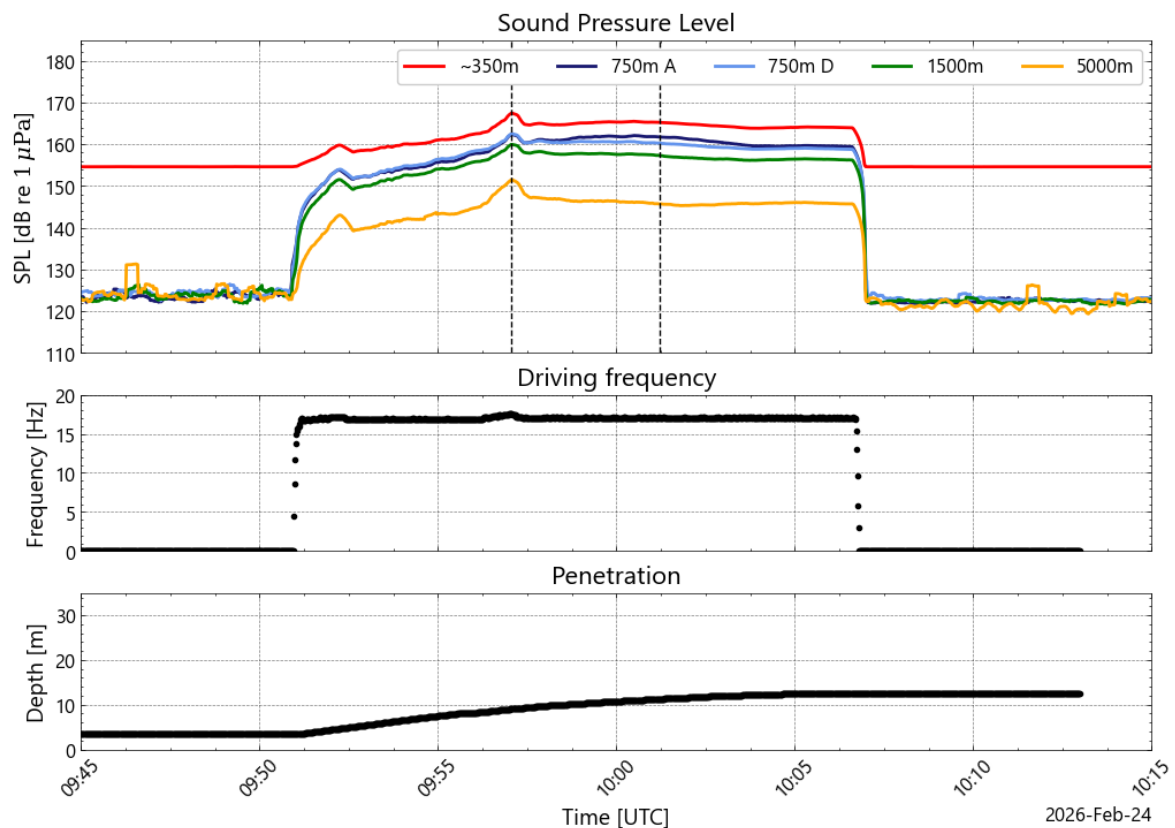


Figure 5.1: Broadband SPL at various distances to the pile, along with the driving frequency and the penetration depth.

For the first 10 m of penetration, the SPL increases with penetration depth. From 10 m until refusal, the SPL changes very little. A short peak in the driving frequency from 17 Hz to 17.6 Hz is accompanied by a peak in the SPL, showing that the generated noise is very sensitive to the driving frequency.

Most of the sound produced during this peak in the driving frequency is produced in frequency bands below 250 Hz (Figure 5.2). The sound is tonal in nature, showing peaks at multiples of the driving frequency. There is an additional peak in the SPL spectrum at 5 kHz

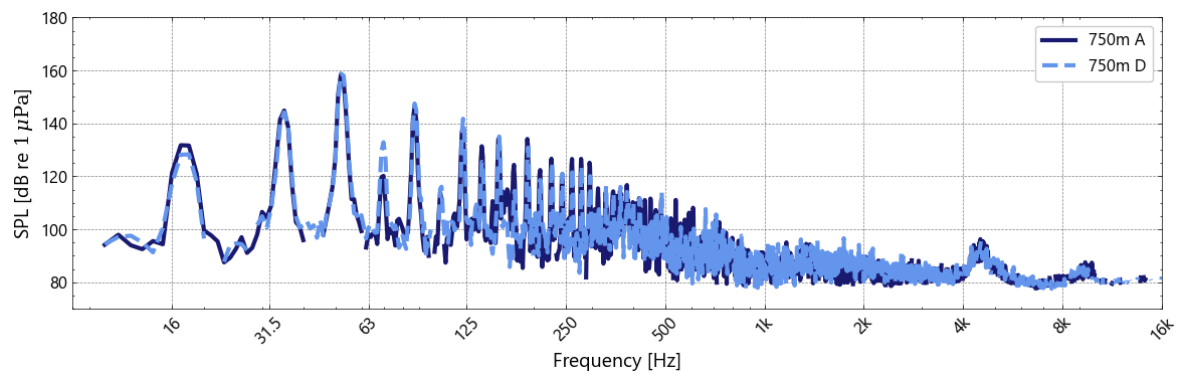


Figure 5.2: Hybrid milidecade SPL spectra at 750m from the pile during the peak in SPL associated with the peak in driving frequency.

Zooming in on the SPL spectrum between 8 Hz and 500 Hz (Figure 5.3) emphasises the spectrum's tonal nature. The spectrum shows peaks at the driving frequency of 17.6 Hz and its harmonics. The third harmonic dominates the overall sound level. The fundamental frequency is likely less prominent due to the limited propagation of the 17.6Hz wave in a depth of less than 30 m. Another possibility is that the third harmonic arises through a hammer-pile-crane interaction: this harmonic may be amplified if it happens to be close to the system's eigenfrequency.

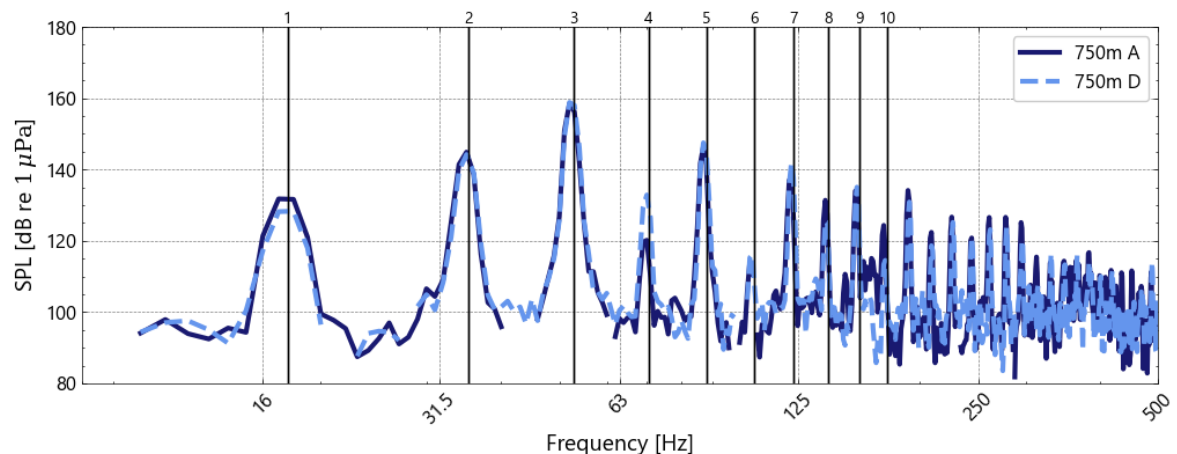


Figure 5.3: Hybrid milidecade SPL spectra at 750m from the pile between 8 Hz and 500 Hz.

The SPL spectrum during driving at 17 Hz (Figure 5.4) shows similar tonal behaviour. One difference with the SPL spectrum at 17.6 Hz is that the fifth harmonic is more prominent at 17 Hz. A more thorough analysis on this spectral behavior is warranted for future research.

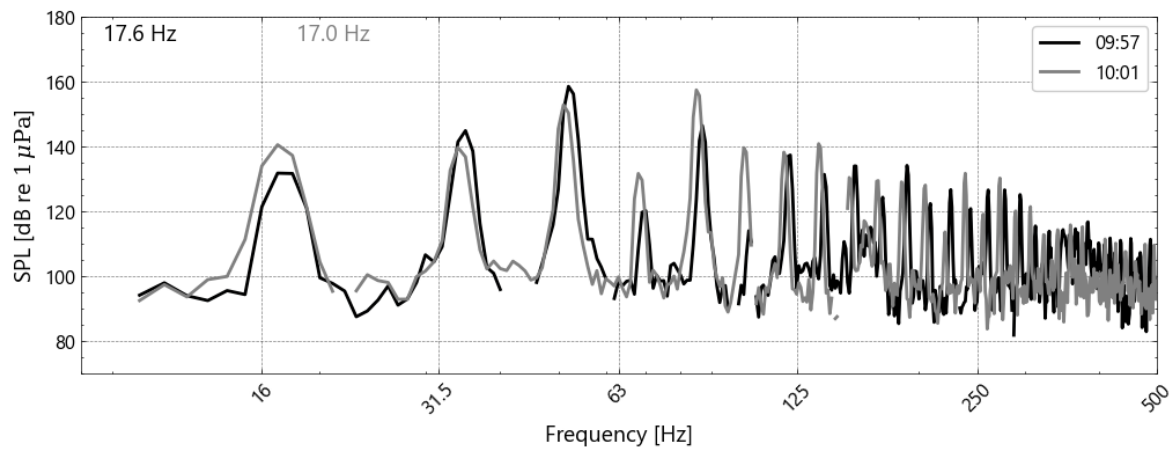


Figure 5.4: Hybrid millidecade spectra of the SPL at 750m from the pile. The spectra shown are indicated by the black dashed lines in Figure 5.1.

In-field propagation (Figure 5.5) shows a spectral decrease of the SPL with increasing distance. The fundamental frequency shows a larger decrease than many of the harmonics.

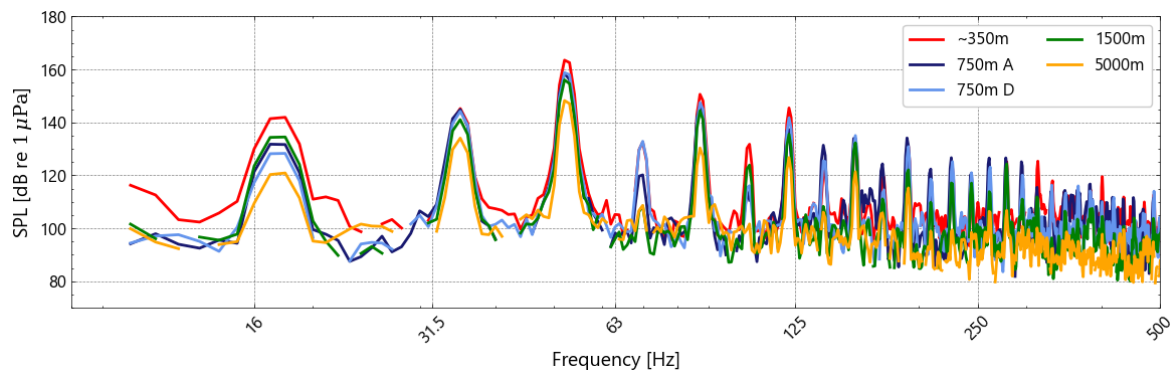


Figure 5.5: Hybrid millidecade spectra of the SPL at different distances from the pile.

5.2 F1, scenario 6

Scenario 6 concerns vibro driving with the HSD-net deployed. Vibro pile F1 was driven on the 18th of March 2026 between roughly 12:16 and 12:34 driven to a penetration depth of 20 m until refusal. 5.6 shows the broadband SPL during the installation.

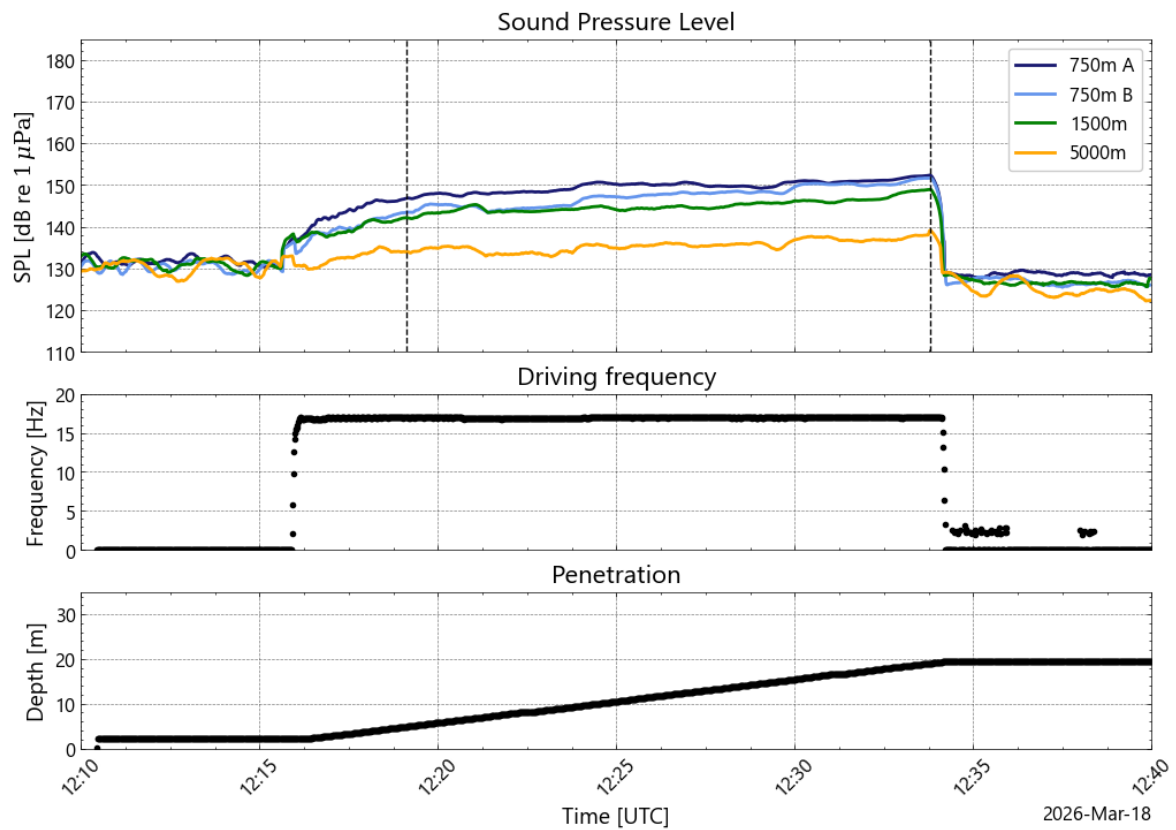


Figure 5.6: Broadband SPL at various distances to the pile, along with the driving frequency and the penetration depth.

Compared to the unmitigated case, vibro driving with a HSD net results in broadband SPL values that are 10 dB lower (8 dB at the same driving frequency). While the driving frequency remains constant, the SPL increases with increasing penetration depth, leading to the preliminary conclusion that seabed transmission becomes more relevant when sound transmission through the water column is mitigated. The maximum SPL occurs just before the vibro tool is turned off. The tonal nature of the sound is visible in the SPL spectrum at this maximum (Figure 5.7).

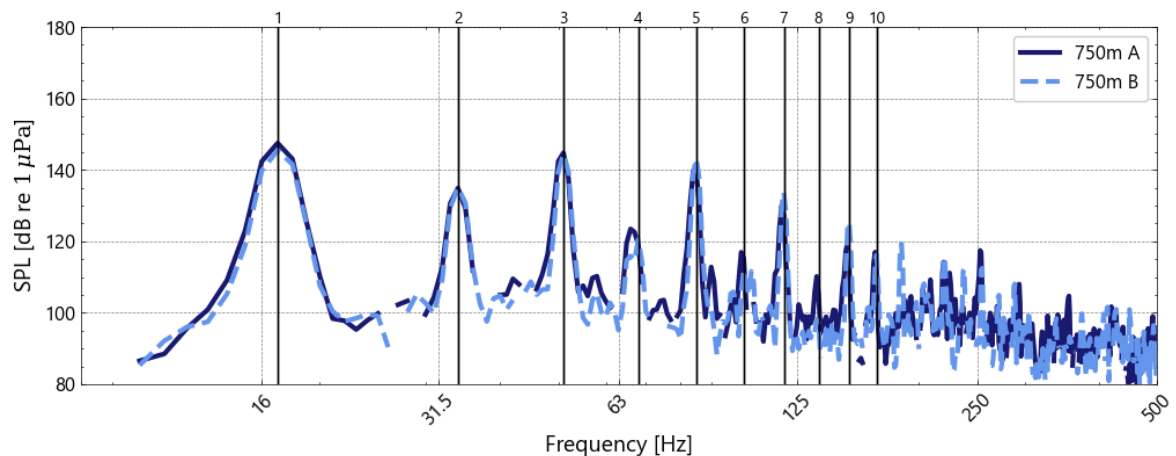


Figure 5.7: Hybrid millidecade SPL spectra at 750m from the pile just before the vibro tool is turned off.

The spectral SPL is reduced compared to the unmitigated case. The effectiveness of the HSD-net (Figure 4.3) can be seen in the results: the fundamental frequency at 17 Hz is dampened less than the third harmonic at 51 Hz.

In-field propagation (Figure 5.8) shows a difference between the SPL spectrum at 750 m and

1500 m that is smaller than expected; this requires further investigation in a follow up report. At 5000 m, the SPL spectrum is close to the background level for frequencies exceeding 250 Hz.

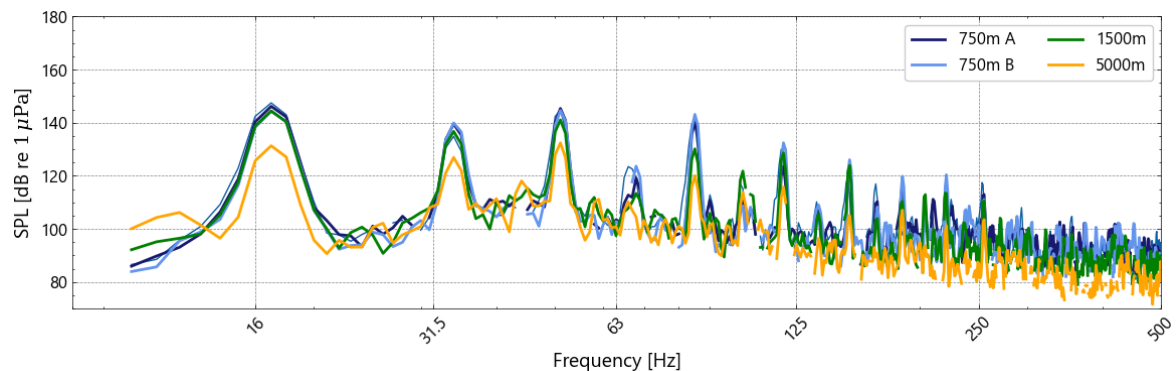


Figure 5.8: Hybrid millidecade SPL spectra at different distances from the pile just before the vibro tool is turned off.

A comparison between the SPL spectra at low and high penetration depths (Figure 5.9) shows that the increase of broadband SPL with increasing penetration depth is due to an increase in the fundamental frequency. This is another indication of the importance of seabed transmission in the presence of mitigation measures.

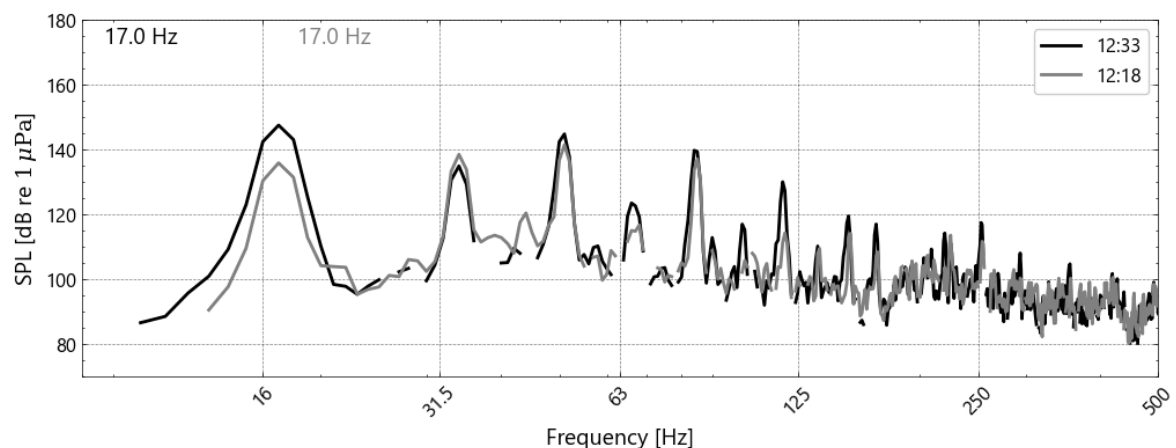


Figure 5.9: Hybrid millidecade SPL spectra at different times and penetration depths. The spectra are taken at the two black dashed lines in Figure 5.6.

A comparison between the SPL spectra with and without HSD net at 10 m penetration depth (Figure 5.10) shows that the HSD net mainly dampens the higher harmonics. This is in line with previous findings.

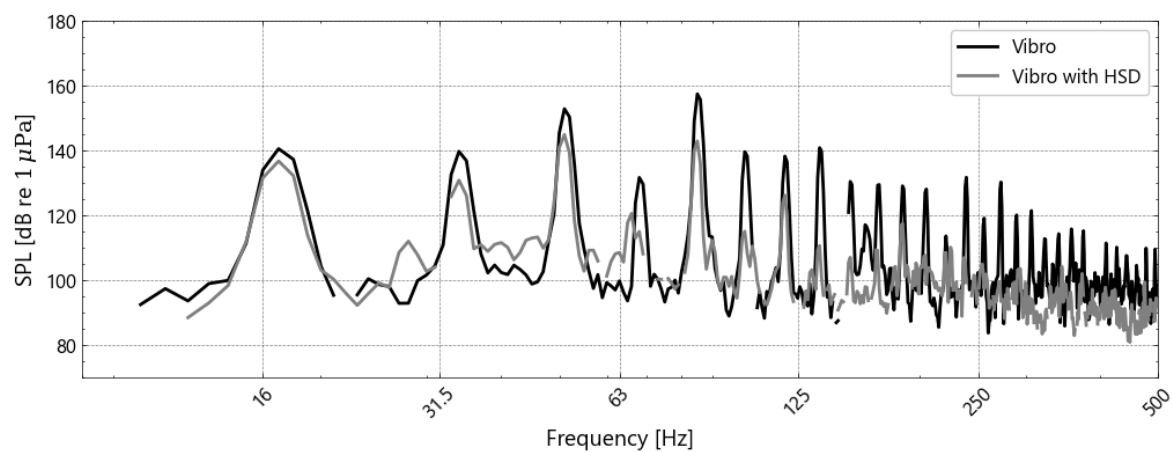


Figure 5.10: Hybrid milidecade spectra of the SPL of vibro with and without the HSD deployed. The spectra are taken at a penetration depth of roughly 10m.

6 VIBROJET® RESULTS

Three of the piles that were installed in the Ecowende wind farm were Vibrojet® -driven. L3 was the first to be installed and almost reached penetration depth, but was stopped due to the maximum drive time of 40 minutes. L2 and L4 were later installed to their full penetration depth.

6.1 L2, scenario 7

Scenario 7 concerns unmitigated Vibrojet® driving. Vibrojet® pile L2 was driven on the 2nd of April 2026 between roughly 11:51 and 12:35 to a final penetration depth. Figure 6.1 shows the broadband SPL during the installation.

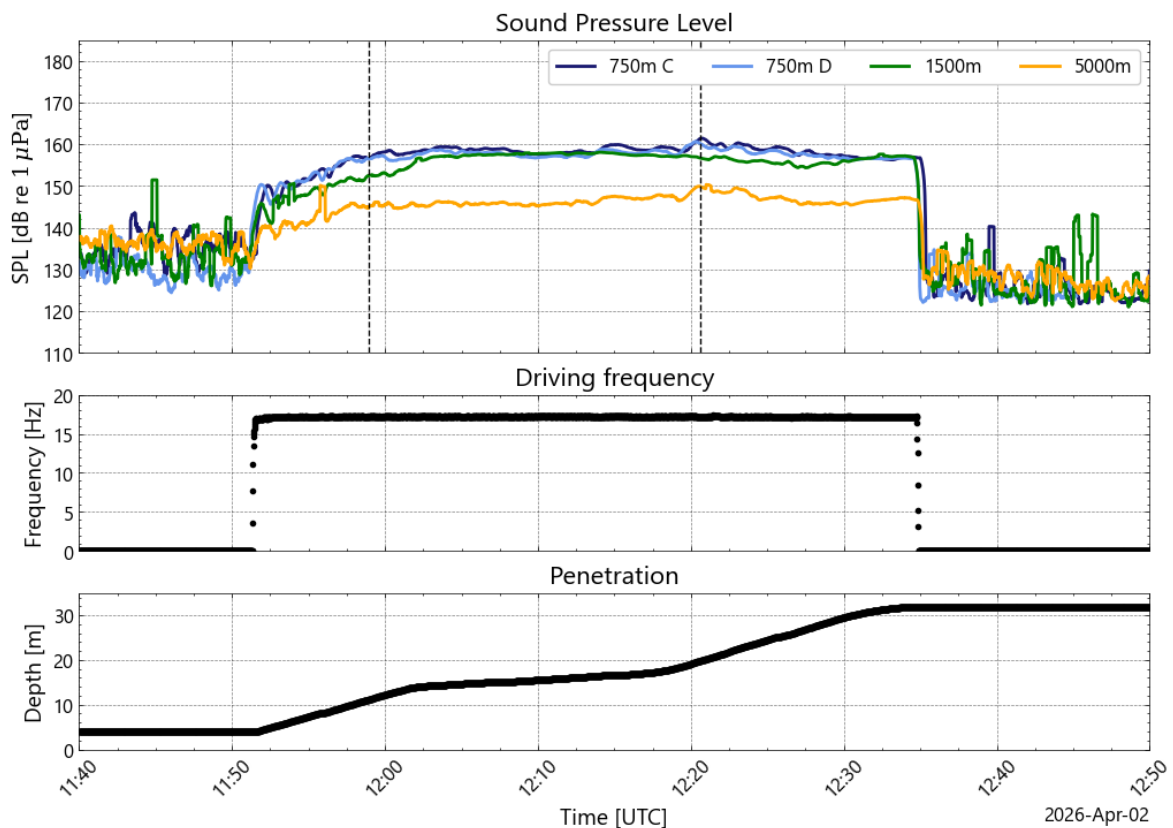


Figure 6.1: Broadband SPL at various distances to the pile, along with driving frequency and the penetration depth.

The SPL initially increases with increasing penetration depth. After this increase, the SPL remains mostly constant. The measured sound at 750 m is close to that measured at 1500 m around 12:10 and after 12:30. The highest broadband SPL value was 161 dB — slightly lower than the highest value for vibro-driving.

The tonal nature of the vibro tool is visible in the SPL spectrum (Figure 6.2), particularly between 8 Hz and 500 Hz (Figure 6.3).

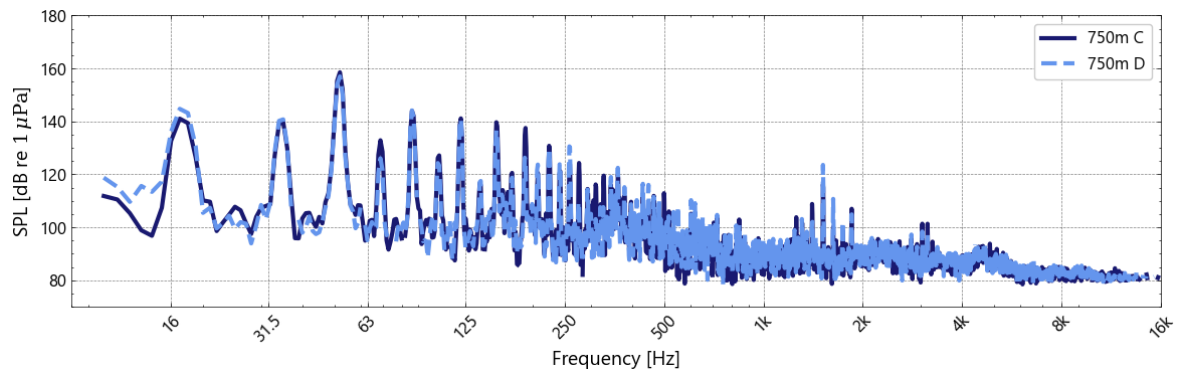


Figure 6.2: Hybrid millidecade SPL spectra of unmitigated Vibrojet®-driving at two locations at 750m from the pile.

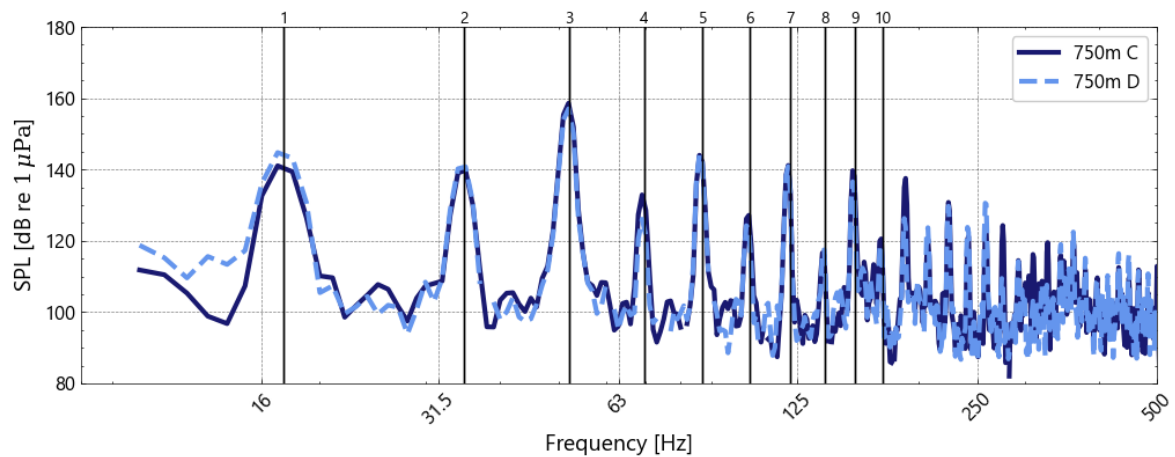


Figure 6.3: Hybrid millidecade SPL spectra at 750m from the pile between 8 Hz and 500 Hz.

Propagation of the Vibrojet® sound (Figure 6.4) is in line with that of vibro sound. The only notable observation is that at the fundamental frequency, the SPL at 1500m exceeds the SPL at 750m. This could be due to seabed transmission or due to other forms of directionality.

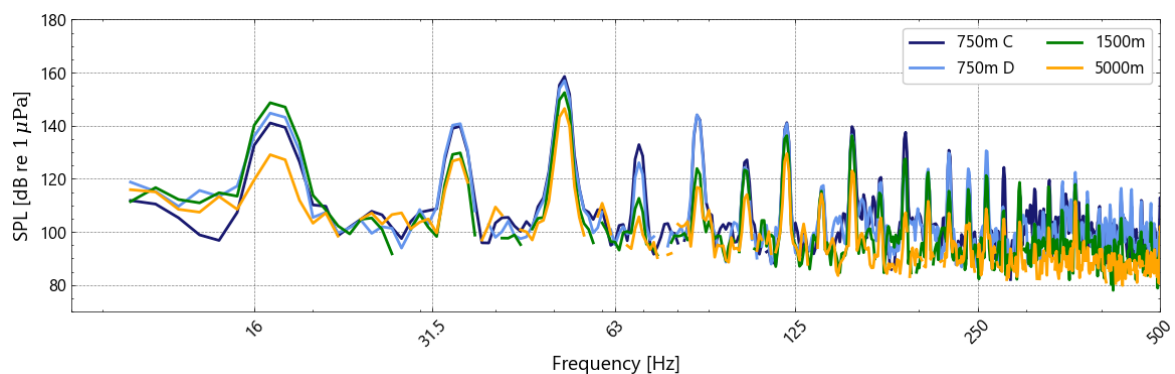


Figure 6.4: Hybrid millidecade SPL spectra at different distances from the pile.

A comparison of the SPL spectrum during the start-up of the Vibrojet®-driving to the SPL spectrum at the peak SPL broadband value (Figure 6.5) shows that the increase in broadband SPL is mainly due to an increase in the SPL at the third harmonic. Tonal features present in both spectra are seemingly independent on penetration depth and persist throughout the installation

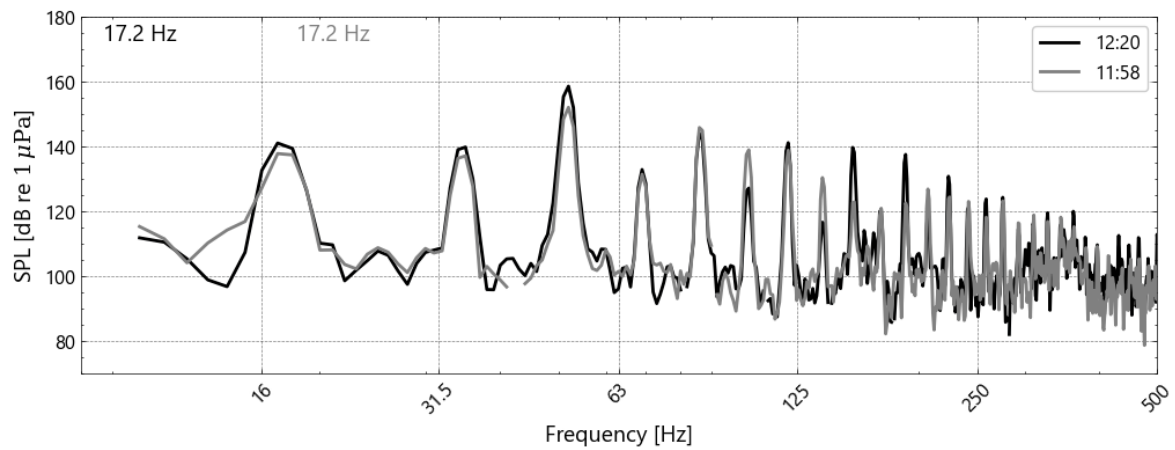


Figure 6.5: Hybrid milidecade spectra of the SPL at different moments of the installation. The spectra are taken at the two black dashed lines in Figure 6.1.

A comparison of the SPL spectra of the vibro-driving and the Vibrojet® -driving (Figure 6.6) shows that the dominant third harmonic is nearly identical, resulting in similar broadband SPL values. The main difference between these spectra is between 1 kHz and 3 kHz, where the jet creates audible noise. This addition to the SPL spectrum does not affect the broadband SPL due to the dominant harmonics in the spectrum.

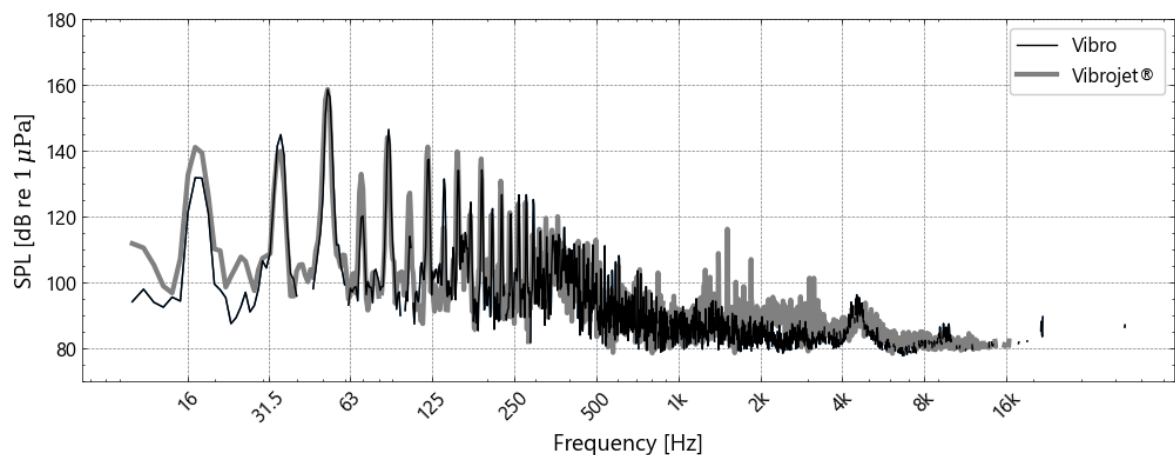


Figure 6.6: Hybrid milidecade spectra of the SPL of vibro driving and Vibrojet® driving at 750m from the pile.

6.2 L3 and L4, scenario 7

The L3 and L4 piles are considered part of the same scenario. Pile L3 was installed on the 29th of March 2026 between roughly 04:19 and 04:59. The final penetration depth was not reached within the maximum 40 minutes of allowed driving. Figure 6.7 shows the broadband SPL during the installation.

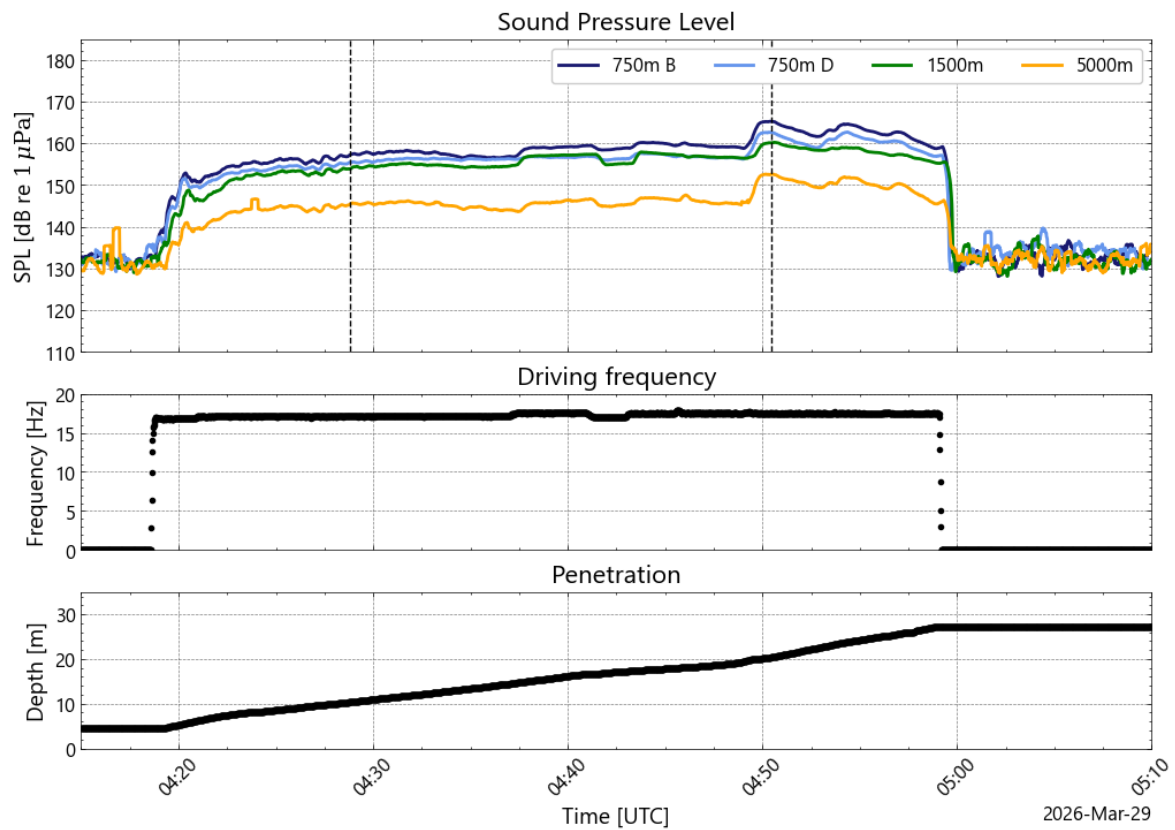


Figure 6.7: Broadband SPL at various distances to the pile, along with driving frequency and the penetration depth.

The increase of the driving frequency at 4:40 resulted in an increase of the SPL, showing that the SPL is sensitive to the driving frequency. The SPL initially increases with increasing penetration depth. At 4:50, the SPL sharply increases to 165 dB. This increase is not linked to the driving frequency or the penetration depth. The hook load (not shown) does increase at this time, and a softer soil layer seems to have been encountered. The second report will investigate this SPL increase in detail. Spectrally, the increase can be attributed to the third harmonic (Figure 6.8).

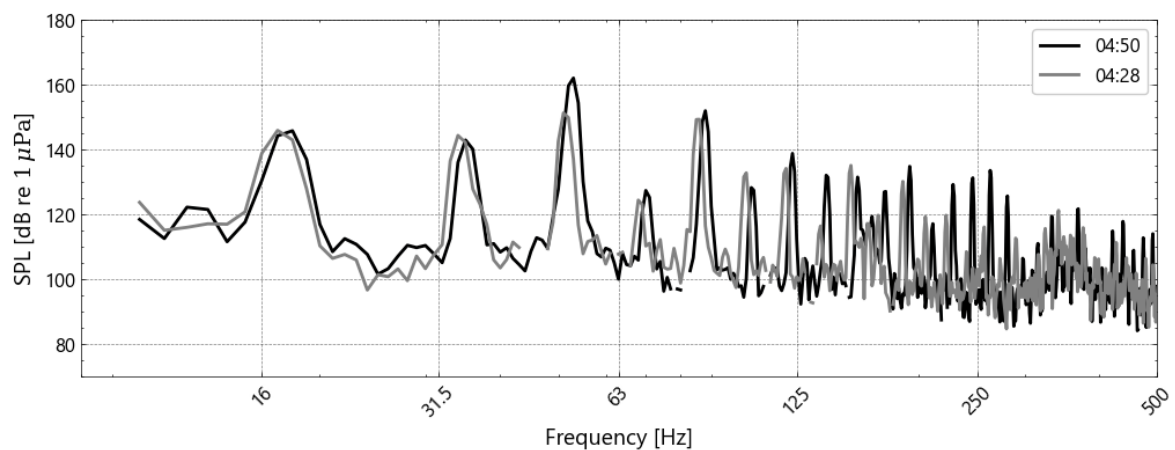


Figure 6.8: Hybrid millidecade SPL spectra of unmitigated Vibrojet®-driving at 4:28 and at 4:50.

The broadband SPL during the installation of L4 (Figure 6.9) shows that the SPL initially increases with increasing penetration depth. After a sharp decrease around 4:20 the SPL increases until 4:42, after which the SPL declines. The maximum measured SPL value during the installation up

to the final penetration depth is 162 dB.

SPL for L4 show the initial increase with penetration depth. Then a sudden drop around 04:20 after which there is a slow but steady increase until about 04:42 after which there is a drop in the SPL. The maximum SPL measured is 162 dB. The pile is installed till final penetration depth.

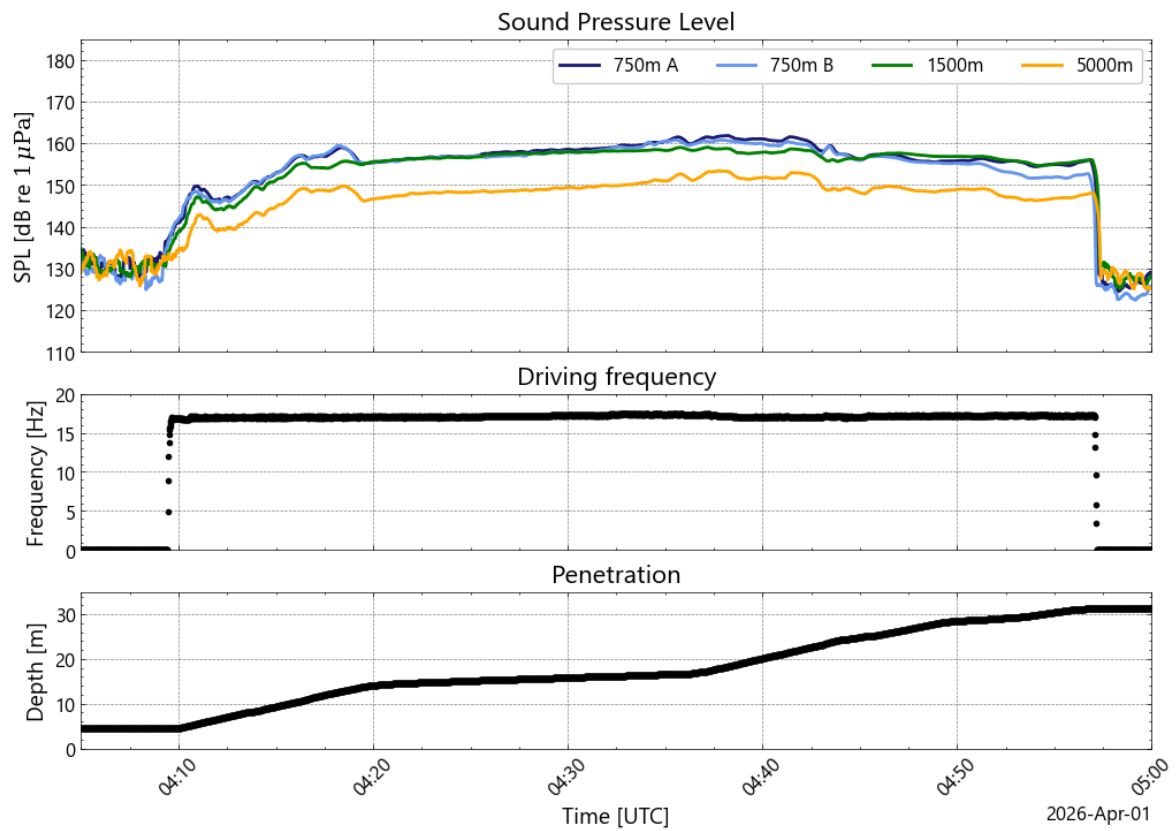


Figure 6.9: Broadband SPL at various distances to the pile, along with driving frequency and the penetration depth.

7 CONCLUSION

This report shows the processed data of the noise monitoring campaign conducted during the installation phase of the Ecowende wind farm. The underwater noise emitted for three different installation techniques, and with the implementation of different mitigation measures, was measured at various distances from the installation locations. Table 7.1 shows the maximum broadband values measured during each scenario. The maximum SEL_{SS} (dB re 1μPa²s) represents unmitigated installation. The maximum SPL (dB re 1μPa) for vibro- and Vibrojet® installations may have occurred at any time during the installation, depending on local conditions and driving frequency.

Table 7.1: Overview of the measured scenarios and the resulting maximum broadband SEL_{SS} or SPL values at 750 m.

Pile ID	Driving type	Scenario	max SEL _{SS}	max SPL
G2	Impact	1a	174 dB	-
G5	Vibro	5	-	-
A1	Impact	1b	178 dB	-
A3	Vibro	5	-	162 dB
A3	Impact	4	175 dB	-
F1	Vibro	6	-	152 dB
L3	Vibrojet®	7	-	165 dB
L4	Vibrojet®	7	-	161 dB
L2	Vibrojet®	7	-	162 dB

The following observations were made from the processed data for impact piling:

- The broadband effectiveness of the dBBC is approximately 12 dB.
- The broadband effectiveness of the HSD net is approximately 8 dB.
- Unmitigated piling (using an MNRU) yields a maximum SEL_{SS} of approximately 178 dB.
- The broadband SPL increases with increasing hammer energy and increasing penetration depth.

The following observations were made from the processed data for vibro- and Vibrojet® -driving:

- Vibro sound is tonal in nature. Its spectrum is dominated by the harmonics of the driving frequency. The third harmonic is dominant in most scenarios.
- The fundamental frequency becomes dominant when a HSD net is used.
- The broadband SPL increases when the driving frequency increases.
- The Vibrojet® SPL spectrum is a combination of the vibro SPL spectrum and the jet spectrum (between 1 kHz and 3 kHz). The broadband SPL is unchanged, due to the dominance of the third harmonic.

A follow up report will provide an in-depth analysis of these data to provide technical insight into some of the open questions following from the data processing.

8 OUTLOOK TO THE SECOND REPORT

This first report has focused on the processing of the data that was gathered during the noise monitoring campaign. A basic interpretation of the data was also given. This interpretation should be considered a quality check on the data; it was determined that the gathered data has enough information of sufficient quality to answer more fundamental questions.

The second report will focus on the interpretation of the results. A more thorough analysis of the effectiveness of the mitigation measures will follow: including:

- In-depth analyses of the effectiveness of the HSD-net
- In-depth analyses of the effectiveness of the dBBC, including a direct comparison of the measurements inside and outside the deployed bubble curtains. This includes an analysis of the changing signature of the sound impulses to practically isolate the dBBC effect on the blows. These comparisons will also provide insight on the sound energy transmitted through the seabed underneath the bubble curtain.
- Temporal variability in the effectiveness of the bubble curtain. Variations in the effectiveness are likely, in particular for the dBBC, due to changing air distribution. Variability of the effectiveness is relevant for reliable compliance to regulations.
- Analyses to determine the origin of insertion loss across the frequency range for bubble curtains (e.g. linked to air bubble diameter) and HSDs (e.g. due to stiffness and size of structures in the system).

The characteristics of the emitted noise for the innovative installation techniques are further analysed. These analyses will focus on identifying the key mechanisms that impact emitted noise for both techniques. The impact of innovative/alternative installation techniques on the emitted noise and resulting impact on marine life is currently included in the KEC and EIAs with many assumptions. Noise emitted during foundation installations using these techniques is expected to result in less impact on marine life, but comparing impact of conventional versus innovative installation techniques is not straightforward. The measured sound levels will be analysed in more detail to determine sound characteristics and relevant scaling parameters. The results will be used to validate and further improve empirical predictive scaling laws that are currently applied in the KEC methodology. Analysed sound levels will be translated to harbour porpoise disturbance days using the latest scientific insights (e.g. research by SEAMARCO) to be able to quantify the reduction in impact in comparison with conventional installation techniques.

The dataset includes measurements collected at 1500 m and 5000 m, which combined with the PAM network will provide insight into the propagation of sound into the environment. The propagation models that are applied in the KEC approach are validated on a very limited number of measurements. This unique dataset provides measurements close to the sound source as well as measurements at distances of more than 10 km from the foundation to further validate and improve the applied propagation models.

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